A Hierarchical and Modular Resource Management in the Future Wireless Systems

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Abstract

The recent evolution of mobile wireless systems into Heterogeneous Networks (HetNet), along with the introduction of the 5th Generation (5G) systems, significantly increased the complexity of the resource management. The current mobile network landscape consists of multitude of system features, spectrum bands, use cases, licensing schemes, radio technologies and network layers. Recent trends show that the increased traffic demand is uneven in terms of spatial and temporal domains, calling for a dynamic approach to resource allocation. To cope with those complexities, a generic and adaptive scheme is required for efficient operation of those networks.

This dissertation proposes to use a hierarchical and modular framework as an approach to cover the mentioned challenges and generalize this scheme to different network layers. After a short overview, stating the problem and potential solutions, the author discusses in details the fragmentation of solutions and system features in the current networks, summarizing this by means of Spectrum Toolbox, a method allowing to categorize the complex system's landscape.

Next, a generic scheme is proposed to cope with this complexity. The proposed management solution is based on three main components: *specialized solutions* for individual requirements, exposed to the *unified generalized layer,* which acts as a coordinator, through a proper *abstraction layer*. In this approach, the specifics are separated from the system's coordination and new items can be added as "plugins" to the architecture. The resulting framework is hybrid and aims at simplification of the introduction of new elements.

The proposed scheme is then verified with the examples of solutions at different network layers, including the Unified MAC layer, Unified Traffic Steering and Generalized Radio Environment Maps. This discussion is based on the author's experience from different commercial and non-commercial projects, which resulted in respective publications.

Finally, a potential further work is proposed to further generalize the solution towards other network layers, especially in the era of Software-Defined Networking.

Streszczenie

Ewolucja mobilnych systemów bezprzewodowych w kierunku sieci heterogenicznych (HetNet) wraz z wprowadzeniem systemów piątej generacji (5G) znacznie zwiększa złożoność zarządzania zasobami. Na obecny kształt sieci mobilnych składa się: wiele pasm, podsystemów i funkcji, usług, sposobów licencjonowania, technologii radiowych itp. Dodatkowo zwiększone zapotrzebowanie na pojemność systemu rozłożone jest nierównomiernie w czasie i przestrzeni, co wymaga dynamicznego podejścia do alokacji zasobów radiowych. Aby poradzić sobie z tymi wyzwaniami, wymagane są adaptacyjne metody zarządzania sieciami dla zwiększenia efektywności wykorzystania zasobów.

W rozprawie zaproponowano zastosowanie hierarchicznej i modułowej struktury jako podejścia do zaadresowania wspomnianych wyzwań i uogólnienia tego podejścia na różne warstwy sieciowe. Po krótkim przeglądzie opisującym problem i potencjalne rozwiązania, autor szczegółowo omawia różnorodność rozwiązań w obecnych sieciach mobilnych, podsumowując to przy użyciu schematu nazwanego *Spectrum Toolbox*, klasyfikującego różne aspekty rozważanych systemów.

Następnie autor przedstawia uogólniony schemat podejścia do tematu złożoności w sieciach radiowych. Proponowane rozwiązanie do zarządzania zasobami opiera się na trzech głównych komponentach: grupie wyspecjalizowanych rozwiązań, warstwę abstrakcji oraz warstwę ujednoliconą, pełniącą funkcję koordynatora. W tym podejściu szczegóły są oddzielone od mechanizmów koordynacji, a nowe elementy można dodawać jako „wtyczki" do architektury. Powstała struktura jest hybrydowa i ma na celu uproszczenie wprowadzania nowych rozwiązań.

Następnie zaproponowana architektura została zweryfikowana za pomocą przykładów rozwiązań na różnych warstwach sieci, w tym: *Unified MAC layer*, *Unified Traffic Steering* oraz *Generalized Radio Environment Maps*. Przedstawiona analiza opiera się na doświadczeniu autora z komercyjnych i niekomercyjnych projektów, które zaowocowały odpowiednimi publikacjami, będącymi częścią niniejszej dysertacji. Na koniec przedstawiono potencjalne kierunki rozwoju nad dalszym uogólnieniem rozwiązania na inne warstwy systemowe.

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My special thanks go to the professors at the Poznan University of Technology, who supported my efforts, namely prof. Hanna Bogucka and prof. Krzysztof Wesołowski.

I would also like to thank my colleagues, with whom I have had the great pleasure to work along my career, and especially to those who took the time to help me when I was preparing this dissertation despite their duties, including: Mateusz Buczkowski, Malek Cellier, Ivan Gaspar, Martin Kasparick, George Koudouridis, Paweł Kryszkiewicz, Dimitri Ktenas, Łukasz Kułacz, Nicola Michailow, Christer Qvarfordt, Moe Rahnema, Frank Schaich, Kamil Sorokosz, Michal Szydełko, Per Tengkvist, Thorsten Wild and Gerhard Wunder.

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And finally, my ultimate gratitude goes to my parents, who have always supported me and pushed me to reach higher levels.

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List of Abbreviations

1G	1^{st} Generation
2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	3^{rd} Generation Partnership Project
4G	4^{th} Generation
5G	5^{th} Generation
5GC	5G Core Network
5GNOW	5G Non-Orthogonal Waveforms
6G	6^{th} Generation
AAS	Advanced Antenna Systems
AC	Admission Control
ANR	Automatic Neighbor Relationship
ASA	Authorized Shared Access
ATA	Autonomous Timing Advance
BFDM	Bi-orthogonal Frequency Division Multiplexing
BLER	Block Error Rate
CA	Carrier Aggregation
CBRS	Citizens Broadband Radio Service
CC	Congestion Control or Component Carrier
CCO	Capacity and Coverage Optimization
CIO	Cell Individual Offset
CN	Core Network
COC	Cell Outage Compensation
CoMP	Coordinated Multipoint Transmission/Reception
CP	Control Plane
CS	Circuit Switched
D2D	Device-to-Device
DC	Dual Connectivity
DL	Downlink
D-PRACH	Data-Physical Random-Access Channel
DU	Dense Urban
EB	Elevation Beamforming
eICIC	enhanced Inter-Cell Interference Coordination
eIMTA	enhanced Interference Mitigation and Traffic Adaptation

eMBB	enhanced Mobile Broadband
eMTC	enhanced Machine Type Communications (also called LTE-M)
eNB	evolved NodeB
EPC	Evolved Packet Core
ePDCCH	enhanced Physical Downlink Control Channel
ESM	Energy Saving Management
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FBMC	Filter-Bank Multi-Carrier
FDD	Frequency Division Duplex
FD-MIMO	Full-Dimension MIMO
FR	Frequency Range
GFDM	Generalized Frequency Division Multiplexing
HetNet	Heterogeneous Network
HW	Hardware
ICIC	Inter-Cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
IMS	IP Multimedia Subsystem
IMT-2020	International Mobile Telecommunications-2020 (also known as
IMT-Advanced	International Mobile Telecommunications-Advanced (also known
IoT	Internet-of-Things
IP	Internet Protocol
ITU-R	International Telecommunication Union – Radiocommunication
KPI	Key Performance Indicator
LA	Link Adaptation
LAA	License-Assisted Access (also known as LTE-LAA)
LBT	Listen-Before-Talk
LSA	License Shared Access
LTE	Long Term Evolution
LTE-A	LTE-Advanced
LWA	LTE-WLAN Aggregation
LWIP	LTE-WLAN Radio Level Integration with IPsec Tunnel
MAC	Medium Access Control
MBB	Mobile Broadband
MCD	Measurement Capable Device
MCG	Master Cell Group
MD-RSM	Multi-Dimensional RSM
MDT	Minimization of Drive Tests

MIMO	Multiple-Input Multiple-Output
MLB	Mobility Load Balancing
MM	Mobility Management
MME	Mobility Management Entity
mMTC	massive MTC
mmWave	millimeter Wave
MNO	Mobile Network Operator
MR-DC	Multi-RAT Dual Connectivity
MRO	Mobility Robustness Optimization
MTC	Machine Type Communications
NaaS	Network-as-a-Service
NAS	Non-Access Stratum
NB-IoT	Narrowband-IoT
NFV	Network Functions Virtualization
NG-RAN	Next Generation-RAN
NR	New Radio (also known as 5G-NR)
NSA	Non-Standalone
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PC	Power Control
PCell	Primary Cell
PCG	Primary Cell Group
PCI	Physical Cell Identifier
PDCP	Packet Data Control Protocol
PDU	Packet Data Unit
PF	Proportional Fair
PHY	Physical Layer
PoP	Point-of-Presence
PRB	Physical Resource Block
PS	Packet Switched
QoS	Quality
RACH	Random Access Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RCLWI	RAN-Controlled LTE-WLAN Interworking
Rel	Release (e.g. Rel-13)
REM	Radio Environment Map
RO	RACH Optimization

RR	Round Robin or Radio Resources
RRC	Radio Resource Control
RRM	Radio Resource Management
RSM	Radio Service Map
SA	Standalone or System Architecture
SBA	Service-Based Architecture
SC	Small Cell
SCG	Secondary Cell Group
SDL	Supplemental Downlink
SDN	Software-Defined Network
SGW	Serving Gateway
SINR	Signal-to-Interference-and-Noise-Ratio
SL	Sidelink
SON	Self-Organizing Network
SUB	Suburban
SW	Software
TB	Transport Block
TDD	Time-Division Duplex
TS	Traffic Steering
UDN	Ultra-Dense Network
UE	User Equipment
UFMC	Universal Filtered Multi-Carrier
UL	Uplink
UP	User Plane
URLLC	Ultra-Reliable and Low-Latency Communications
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
UTS	Unified Traffic Steering
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Anything
VoIP	Voice-over-IP
WLAN	Wireless Local Area Network

List of Publications

The basis for the Doctoral Dissertation

In accordance with the Polish Act of 14 March 2003 on academic degrees and academic title, and on degrees and title in the field of art (Journal of Laws 2003 No. 65 item 595) Art. 13, section 2. *"The doctoral dissertation may take the form of a manuscript of a book, a book published or a thematically consistent set of chapters in published books, a thematically coherent set of articles published, or accepted for publication, in scientific journals, specified by the minister competent for science on the basis of regulations regarding science financing, if it meets the conditions set out in section 1."*

According to the above, this dissertation consists of a thematically consistent set of publications (provided in *Part B* as the basis for this thesis), accompanied by a description of the main achievement (provided in *Part A*). Those publications (and thus the thesis itself) are the result of the author's research and study in the field of radiocommunication, undertaken during the last eight years, which started with the works on 5G since its early research phase in 2012. Research was concluded, among others, within EU-funded projects, namely FP7 5GNOW and FP7 SOLDER. Beyond those collaborative funded research projects, a significant number of the included articles is a result of the author's involvement in the works on: a holistic framework for the implementation of the LTE-Advanced Pro features, including Licensed-Assisted Access (LAA), LTE-WLAN Aggregation (LWA), Dual Connectivity (DC) and Carrier Aggregation (CA); evaluation of Narrowband Internet-of-Things (NB-IoT) implementation within the LTE system framework; the design of 5G scheduler and network slicing within the 5G Radio Access Network (RAN) architecture; the collaborative research project on Radio Environment Maps (REM) for 5G scenarios in the tier 1 vendor's Research and Development (R&D) office; implementation of the L2/L3 protocol stack on the LTE radio interface; the design and providing technical trainings in the area of LTE, LTE-Advanced, Radio Resource Management (RRM), Self-Organizing Networks (SON) for operators, vendors, R&D institutions in the Netherlands, Saudi Arabia, Sweden, Spain and Poland.

I. Journals and magazines (peer-reviewed)

1. Gerhard Wunder, Peter Jung, Martin Kasparick, Thorsten Wild, Frank Schaich, Yejian Chen, Stephan ten Brink, Ivan Gaspar, Nicola Michailow, Andreas Festag, Luciano Mendes, Nicolas Cassiau, Dimitri Kténas, **Marcin Dryjanski**, Slawomir Pietrzyk, Bertalan Eged, Peter Vago, Frank Wiedmann, *"5GNOW: Non-Orthogonal, Asynchronous Waveforms for Future Mobile Applications"*, IEEE Communications Magazine (Vol. 52, Issue 2, February 2014), DOI: 10.1109/MCOM.2014.6736749, ISSN: 1558-1896

   Impact factor: 4.007 (ref. JCR 2014) *MNiSW points:* 45
   Paper citations: 716 (ref. GoogleScholar) *Patent citations:* 5 (ref. IEEExplore)
   Individual contribution: 5% (considering large number of authors - 18),
   Marcin Dryjański was responsible for: document review; discussion on the contents of this article; contribution to the text in the area of RACH and MAC layer aspects.

2. **Marcin Dryjański**, Michał Szydełko, *"A Unified Traffic Steering Framework for LTE Radio Access Network Coordination"*, IEEE Communications Magazine (Vol. 54, Issue 7, July 2016), DOI: 10.1109/MCOM.2016.7509383, ISSN: 1558-1896,

   Impact factor: 10.435 (ref. JCR 2016) *MNiSW points:* 45
   Paper citations: 11 (ref. GoogleScholar)
   Individual contribution: 60%
   Marcin Dryjański was responsible for: cooperation and discussions during the overall publication structure, concept, and contents of the individual chapters; description of part of the functionality set being the elements of the Unified Traffic Steering and elements of spectrum access methods; developments of the Unified Traffic Steering framework concept, state machine and methodology for the state transitions; participating in the analysis of the individual functionalities in the overall Unified Traffic Steering framework construction; cooperation on the on the use case development; technical coordination of the UTS framework project.

3. Michał Szydełko, **Marcin Dryjański**, *"3GPP Spectrum Access Evolution Towards 5G"*, EAI Endorsed Transactions on Cognitive Communication (12 2016 - 02 2017, Vol. 3, Issue 10), DOI: 10.4108/eai.23-2-2017.152184

   Paper citations: 3 (ref. GoogleScholar)
   Individual contribution: 40%
   Marcin Dryjański was responsible for: cooperation and discussions during the overall publication structure, concept, and contents of the individual chapters; development of the spectrum access methods table; review of the other author's contribution; description of the part of the functionality set being elements of the Spectrum Toolbox concept; cooperation on the description of the future of spectrum access methods.

4. Paweł Kryszkiewicz, Adrian Kliks, Łukasz Kułacz, Hanna Bogucka, George P. Koudouridis, **Marcin Dryjański**, *"Context-Based Resource Management and Orchestration in 5G Wireless Access Networks"*, Hindawi Wireless Communications and Mobile Computing, Vol. 2018, Article ID 3217315, DOI: https://doi.org/10.1155/2018/3217315

   Impact factor: 1.396 (ref. JCR 2018) *MNiSW points:* 25
   Individual contribution: 15%
   Marcin Dryjański was responsible for: quality review of the overall text, and editorials to individual chapters; cooperation and discussion with the other authors regarding the defined solutions and use cases; taking part in the discussions regarding the results analysis; management of the collaboration R&D project, where one of the results was this publication.

II. Articles published in the conference materials (peer-reviewed)

1. Gerhard Wunder, Martin Kasparick, Stephan ten Brink, Frank Schaich, Thorsten Wild, Ivan Gaspar, Eckhard Ohlmer, Stefan Krone, Nicola Michailow, Ainoa Navarro, Gerhard Fettweis, Dimitri Ktenas, Vincent Berg, **Marcin Dryjanski**, Slawomir Pietrzyk, Bertalan Eged, *"5GNOW: Challenging the LTE Design Paradigms of Orthogonality and Synchronicity"*, IEEE VTC, Dresden, Germany, 2-5 June 2013, DOI: 10.1109/VTCSpring.2013.6691814, ISBN: 978-1-4673-6337-2

   Paper citations: 123 (ref. GoogleScholar)
   Individual contribution: 5% (considering large number of authors - 16),
   Marcin Dryjański was responsible for: quality review of the whole article and edits of the sections related to 3GPP standardization; contribution to the text in the field of 3GPP standardization.

2. Gerhard Wunder, Martin Kasparick, Thorsten Wild, Frank Schaich, Yejian Chen, Stephan Ten Brink, Ivan Gaspar, Nicola Michailow, Ainoa Navarro, Gerhard Fettweis, Nicolas Cassiau, Dimitri Ktenas, **Marcin Dryjanski**, Slawomir Pietrzyk, Bertalan Eged, *"5GNOW: Application Challenges and Initial Waveform Results"*, Proceedings of Future Network & Mobile Summit 2013 (FuNeMS'13), Lisbon, Portugal, 3-5 July 2013

   Paper citations: 12 (ref. GoogleScholar)
   Individual contribution: 5% (considering large number of authors - 15),
   Marcin Dryjański was responsible for: review of the whole article; discussions regarding the implementation of MAC scheduling framework on top of the flexible waveforms to make sure that various traffic types can be managed efficiently; contribution to the text in the field MAC layer aspects.

3. Gerhard Wunder, Martin Kasparick, Stephan ten Brink, Frank Schaich, Thorsten Wild, Yejian Chen, Ivan Gaspar, Nicola Michailow, Gerhard Fettweis, Dimitri Ktenas, Nicolas Cassiau, **Marcin Dryjanski**, Kamil Sorokosz, Slawomir Pietrzyk, Bertalan Eged,

“System-level interfaces and performance evaluation methodology for 5G physical layer based on non-orthogonal waveforms”, 2013 Asilomar Conference on Signals, Systems and Computers (IEEE), 3-6 Nov. 2013, Pacific Grove, CA, USA, DOI: 10.1109/ACSSC.2013.6810581, ISBN: 978-1-4799-2390-8

Paper citations: 9 (ref. GoogleScholar)
Individual contribution: 15%
Marcin Dryjański was responsible for: contributing to the text in parts discussing system level simulations and results analysis; contributing to the design of the methodology and configuration system level simulations; running simulations; processing and analysis of the results; taking part in the design of the simulation model of the PHY layer abstraction with FBMC technology to be implemented within the system level simulator.

4. Thorsten Wild, Gerhard Wunder, Frank Schaich, Yejian Chen, Martin Kasparick, **Marcin Dryjanski**, Slawomir Pietrzyk, Nicola Michailow, Maximilian Matthé, Ivan Gaspar, Ainoa Navarro, Luciano Mendes, Andreas Festag, Gerhard Fettweis, Jean-Baptiste Doré, Nicolas Cassiau, Dimitri Kténas, Vincent Berg, Bertalan Eged, Peter Vago, *“5GNOW: Intermediate Transceiver and Frame Structure Concepts and Results”*, Proceedings of the European Conference on Networks and Communications (EuCNC'14), Bologna, Italy, 23-26 June 2014,

   Paper citations: 1 (ref. GoogleScholar)
   Individual contribution: 10%
   Marcin Dryjański was responsible for: quality review of the whole article; contribution to the text in the area of random access, hybrid scheduler concept, network interfaces in 5G system and standardization aspects; design and description of the D-PRACH procedure.

5. Gerhard Wunder, Martin Kasparick, Thorsten Wild, Frank Schaich, Yejian Chen, **Marcin Dryjanski**, Mateusz Buczkowski, Slawomir Pietrzyk, Nicola Michailow,

Maximilian Matthé, Ivan Gaspar, Luciano Mendes, Andreas Festag, Gerhard Fettweis, Jean-Baptiste Doré, Nicolas Cassiau, Dimitri Kténas, Vincent Berg, Bertalan Eged, Peter Vago, *"5GNOW: Intermediate Frame Structure and Transceiver Concepts"*, IEEE Globecom, Austin, TX, USA, 8-12 Dec. 2014, DOI: 10.1109/GLOCOMW.2014.7063492, ISBN: 978-1-4799-7470-2

Paper citations: 24 (ref. GoogleScholar)

Individual contribution: 8%

Marcin Dryjański was responsible for: quality review of the article; taking part in the discussion of the hybrid MAC scheduler design; contribution to the text in the area of hybrid MAC scheduler and network interfaces in the 5G system.

6. Michał Szydełko, **Marcin Dryjański**, *"Spectrum Toolbox Survey: Evolution Towards 5G"*, CrownCom 2016, Grenoble, France, 05.2016. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 172. Springer, Cham, DOI https://doi.org/10.1007/978-3-319-40352-6_58, ISBN: 978-3-319-40352-6

   Individual contribution: 40%

   Marcin Dryjański was responsible for: participating in development of the Spectrum Toolbox concept and development of the evolution table for this concept; description of part of the functionality set being the elements of the Spectrum Toolbox concept, including Carrier Aggregation, Dual Connectivity, License-Assisted Access, LTE-WLAN Aggregation, etc.; review of the other part of functionality set prepared by the other author; description of the further developments of the Spectrum Toolbox concept; cooperation and discussions during the overall publication structure, concept, and contents of the individual chapters.

7. **Marcin Dryjański**, Michał Szydełko, *"Spectrum Aggregation and Management Framework for pre-5G Applications"*, 2016 International Symposium on Wireless Communication Systems (IEEE ISWCS), Poznan, Poland, 20-23 Sept. 2016, DOI: 10.1109/ISWCS.2016.7600958, ISBN: 978-1-5090-2061-4

Paper citations: 1 (ref. GoogleScholar)

Individual contribution: 60%

Marcin Dryjański was responsible for: technical leading of the Unified Traffic Steering framework concept development; strategy definition and mutual dependencies between functions; co-writing of the whole document with different portions in different chapters; cooperation and discussions during the overall publication structure, concept, and contents of the individual chapters; review of the other author's contribution.

8. Per Tengkvist, George P. Koudouridis, Christer Qvarfordt, **Marcin Dryjanski**, Malek Cellier, *"Multi-Dimensional Radio Service Maps for Position-based Self-Organized Networks"*, 2017 IEEE 22nd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), Lund, Sweden, 19-21 June 2017, DOI: 10.1109/CAMAD.2017.8031530, ISBN: 978-1-5090-6302-4

   Paper citations: 3 (ref. GoogleScholar)

   Individual contribution: 15%

   Marcin Dryjański was responsible for: quality review of the overall text, and editorials to individual chapters; contribution to the research work in the scope of the technology and requirements for radio maps and construction of the overall MD-RSM (multi-dimensional radio service maps) concept; contribution to the text as co-author to the requirements section; the description of RSM functionality section, and the enabling technologies section; cooperation and discussion with the other authors on the development of the MD-RSM architecture.

III. Book

1. Moe Rahnema, **Marcin Dryjanski**, *"From LTE to LTE-Advanced Pro and 5G"*, Artech House, US, 2017, 376pp, ISBN: 978-1-63081-453-3

   Individual contribution: 20%

   Marcin Dryjański was responsible for: preparation of the following full chapters: Chapter 13 – "LTE-Advanced Pro: Enhanced LTE Features", Chapter 14 – "Toward 5G"; preparation of parts of the following chapters: "Preface", including overview of the book scope relating to Chapters 13-14, Chapter 1 – "Introduction", including overview of individual Chapters 13-14; quality review of the other chapters.

Collective statistics

- Total Impact Factor: 4.007 + 10.435 + 1.396 = **15.838**
- Weighted sum IF: 4.007 * 0.05 + 10.435 * 0.6 + 1.396 * 0.15 = **6.67075**
- Total number of MNiSW points: 45 + 45 + 25 = **115**
- Weighted sum MNiSW points: 45 * 0.05 + 45 * 0.6 + 25 * 0.15 = **33**
- Total number of citations *(according to GoogleScholar)*: 716 + 123 + 24 + 12 + 11 + 9 + 3 + 3 +1 + 1 = **903**
- h-index *(according to GoogleScholar)*: **7**

Part A

Summary of the main achievement

Chapter I.

Introduction and thesis overview

Over the last decade, mobile networks evolved from a single layer macro-only into Heterogeneous Networks (HetNets) deployments, with the aim of improving the capacity in traffic hotspots. The mobile network's landscape is constantly becoming more complicated due to continuous introduction of new system features, spectrum bands and use cases. Introduction of Small Cells (SC) brought new challenges, including backhaul availability, interference management, mobility management and alike. As the traffic demand in mobile networks is constantly increasing, there is a need for further developments in terms of solutions for local capacity improvements. To address those challenges, spectrum availability, spectral efficiency improvements and higher densification of the radio networks are considered essential with the advent of 5G systems. This calls for more spectrum resources and novel spectrum access schemes, providing higher flexibility of the radio resources allocation.

Looking into the recent advancements within the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE), under the name LTE-Advanced Pro (3GPP Release-13 onwards) [1], it can be seen that it became equipped with multitude of novel functionalities like, Dual Connectivity (DC) enhancements, Carrier Aggregation (CA) enhancements, with the use of up to 32 Component Carriers (CC), Self-Organizing Networks (SON) for Advanced Antenna Systems (AAS) and Full-Dimension MIMO (FD-MIMO). Another set of features under the Rel-13 considerations include the aggregation of licensed and unlicensed spectrum. In this context, from the one side, the Wi-Fi technology is used with the following solutions: LTE-Wireless Local Area Network (WLAN) Aggregation (LWA), LTE-WLAN Radio Level Integration with IPsec Tunnel (LWIP) and RAN-Controlled LTE-WLAN Interworking (RCLWI) [2]. Those three features address the same aspect, i.e. the tight Wi-Fi interworking with the 3GPP Radio Access Network (RAN), but require different upgrades to the Wi-Fi network and to the User Equipment (UE). On the other end of the unlicensed spectrum usage modes, the resources from licensed and unlicensed spectrum can be aggregated, exploiting the CA framework under the Licensed-Assisted Access (LAA) scheme, where the tailored version of LTE radio interface has been designed for support, e.g. Listen-Before-Talk (LBT) mechanism [3]. Narrowband Internet-of-Things (NB-IoT) addresses the need for low-power Machine-Type Communications (MTC) through the lean air interface using 180 kHz carriers and network optimizations, enabling the transmission of the short packets over Non-Access Stratum (NAS) [4]. The Device-to-Device (D2D) and Sidelink (SL) design enables to utilize the direct communication between UEs within the LTE coverage or out-of-coverage to enable both public safety and commercial services [5]. The vehicular communication is being addressed within the Release 14, building upon D2D and SL framework, with enhancements targeting Vehicular-to-Vehicular (V2V), Vehicular-to-Network (V2N), Vehicular-to-Infrastructure (V2I) and Vehicular-to-Pedestrian (V2P) services with both collision-avoidance and entertainment types of services.

3GPP has, in parallel to the LTE developments, started the work on the 5G systems already in Release 14. The 5G phase 1 (3GPP Rel-15, which addresses the immediate commercial needs) work has been further split into Non-Standalone (NSA) 5G mode (with the signaling connection being anchored in LTE) and Standalone mode (SA), where the new radio interface provides the signaling connection itself [6]. The International Mobile Telecommunications-2020 (IMT-2020), defined by International Telecommunication Union-Radiocommunication Sector (ITU-R) targets the three key usage scenarios, namely the enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and Ultra-Reliable and Low-Latency Communications (URLLC) [7]. The 5G air interface should, therefore, be able to cope with these use cases and their divergent requirements on high throughput, low latency or massive sporadic transmissions. On top of this, the next generation system should support the large frequency range, from several hundred megahertz up to 100 GHz, taking into consideration the millimeter-wave communication. For this purpose, to capture the differences in propagation and use case requirements, the scalable numerology has been proposed for the New Radio (NR), serving as a new air interface of the 5G system. On the network side, the concept of network slicing has been introduced to capture the differences in the various use cases and to enable optimization of independent logical networks, built upon a single infrastructure [8]. Taking into account the recent Rel-13 and Rel-14 LTE-Advanced Pro improvements described above, it can be seen that some of the use cases envisioned for 5G are addressed by LTE enhancements. For those systems to coexist, a tight interworking between them is an important part of the 5G[1].

All of the above, in turn, provides a landscape of the mobile networks, which increases the overall complexity of a system. This particularly touches the area of Radio Resources Management (RRM) and network management in general (encompassing SON), the complexity of which increases significantly. Whenever a new item (a spectrum band, a spectrum access method, a licensing method etc.) is added, the RRM becomes more fragmented.

A native and unified approach to the coordination of radio access mechanisms in a multi-Radio Access Technology (RAT) network for efficient data delivery is therefore needed. This led the author of this dissertation to state the following research thesis:

PhD Thesis:

The flexibility of the wireless systems, in the context of the services, functionalities, spectrum development and their evolution, is achieved through a unified and hierarchical approach to the resource management.

PhD dissertation goal:

The goal of investigation activities, conducted within this dissertation, is to define a resource management framework for complex wireless systems and generalize this framework for various network layers.

The main contributions of the dissertation are:

- definition of the scope of individual items, which create a problematic landscape in mobile telecommunication systems and classification of the problematic areas. The scientific purpose is to increase the knowledge in the area of the network management and interdependencies between different system feature;

[1] The two consecutive paragraphs are reworked versions of a paragraph from Chapter 1 in [MD3]© Artech House 2017, used with permission of the publisher.

- proposition of a framework capturing the stated problem by hybrid approach to resource management, and determination of the applicability of the proposed solution within the mobile networks;
- proposition of a generalization of the designed solution for applicability to different system layers and providing application examples of the proposed framework. This could contribute to the applicability of the approach to improve the overall system design of future networks.

The dissertation is arranged in the following way: **Chapter II** provides background for the work and states the problem (the author's contribution related to this topic is provided in: **[MD1], [MD2]** and **[MD3]**). **Chapter III** decomposes the mentioned systems' complexity problem by providing an analysis of different aspects and defining the Spectrum Toolbox concept (the author's contribution related to this topic is provided in: **[MD1], [MD2]** and **[MD3]**). **Chapter IV** proposes a design of resource management framework to address the stated problem (the author's contribution related to this topic is provided in: **[MD4]-[MD13]** and in the following supplementary materials: **[MD1supp], [MD2supp]**). **Chapter V** shows examples of the proposed approach in three use cases, namely the Unified Medium Access Control (MAC) design, Unified Traffic Steering (UTS) and hybridization of Radio Environment Maps (REM) (the author's contribution related to this topic is provided in: **[MD4]-[MD13]** and in the following supplementary materials: **[MD1supp], [MD2supp]**). **Chapter VI** formulates a generalization of the proposed framework by extension towards other network layers. Finally, **Chapter VII** summarizes the work.

Chapter II.

Overview of wireless systems' evolution

This chapter provides an overview of the topic and points out the main issues to be addressed within this dissertation. First, the evolution of wireless mobile networks is outlined, followed by an overview of the general system's architecture and RRM aspects. Then, key points related to the complexity of current networks are underlined, and finally, different management approaches to address this complexity are presented.

The author's contribution in the content of this chapter is based on the following publications: **[MD1], [MD2]** and **[MD3]**, with the aim to emphasize key points to be resolved by the resource management framework, which is the goal of this dissertation.

2.1 Evolution of wireless networks

Figure 1 shows the evolution of mobile wireless systems, emphasizing two aspects: first, key services, which those systems were designed to provide; second, a general assumption captured when designing them.

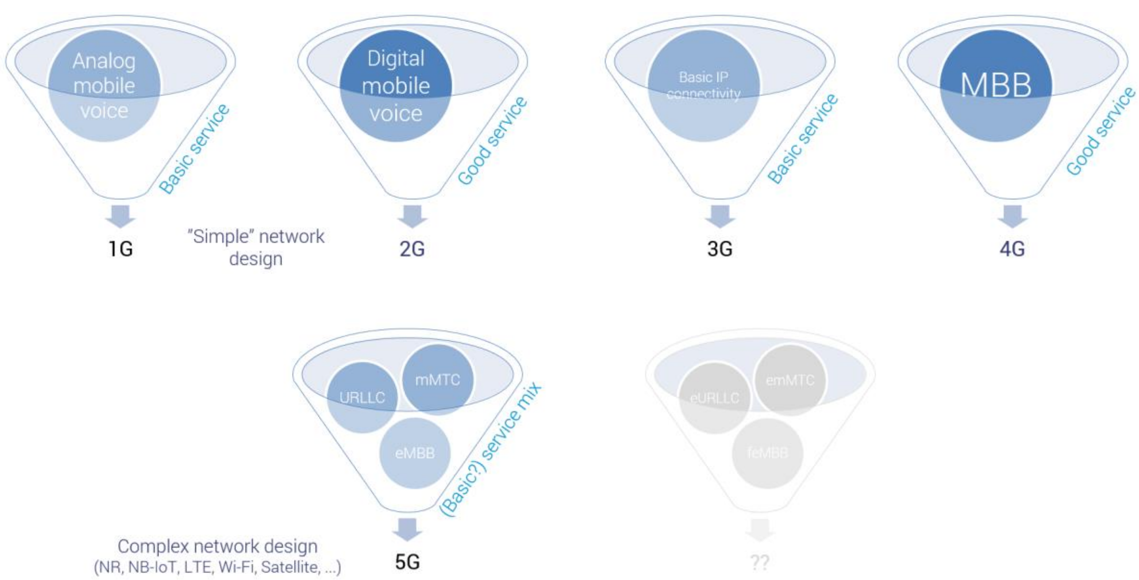

Figure 1. Generations of mobile wireless systems.

The author would like to underline two conclusions that could be drawn from this figure[2]. Firstly, the odd generations provide (to date) an approach to new requirements, along with services that were not present before (e.g., 1G for mobile voice, 3G for mobile Internet access), while the even generations represent the evolution of the odd ones, "correcting" the design of the predecessors to properly deliver the main service. Secondly, until the 4th Generation, the network was designed with a "single" design approach, also known as "one-size-fits-all", because there was a single main service to address (e.g. voice or Internet access). With the emerging 5th Generation (along with the emerging Internet-of-Things (IoT) and new vertical markets, as well as ever-increasing need for capacity and throughput for broadband access) the perspective has changed. In current situation, there is no single "killer application", to be served by the system, but rather the system should be able to cover multitude of services with diverging requirements. Those services, like high throughput mobile broadband (addressed by eMBB), through extremely low latency communications (with URLLC), down to low-end MTC applications with very sporadic transmissions using several bytes (with mMTC), call for support of different connectivity approaches. Thus, the 5G system should be flexible enough to cover those requirements **[MD3]**. Following the conclusions stated above, it can be said, that the 5th Generation of mobile wireless systems is the "odd" version, approaching this collection of services for the first time. Whether there will be a need for 6G to "fix the 5G legacy mistakes" – time will tell – but one thing is certain: without a new approach to the system design, it will be difficult to proceed, in the context of the requirement, that there is no single application or service to focus the efforts on.

2.2 Architecture of cellular networks

The basic components of cellular networks, which are constant through generations, include *air interface* (encompassing the air interface protocol stack, e.g. New Radio (NR), Evolved-Universal Terrestrial Radio Access (E-UTRA) or UTRA), *radio access network*

[2] Disclaimer: this paragraph presents solely the viewpoint of the author of this dissertation and is quite simplified (e.g. does not include all the intermediate steps with the GPRS and HSPA+, which make the transition points from 2G-to-3G and from 3G-to-4G respectively). Other ways of classification of the mobile system generations present in the industry typically consider higher speeds and lower latencies from generation to generation.

(composed of controllers and transmission nodes, combined or split, e.g. Next Generation-RAN (NG-RAN), Evolved Universal Terrestrial Radio Access Network (E-UTRAN) or UTRAN), *core network* (e.g. 5G Core Network (5GC), Evolved Packet Core (EPC), Packet-Switched and Circuit Switched (PS/CS) Core) and *service network* (e.g. Internet, IP-Multimedia Subsystem (IMS)). What differentiates particular mobile network generations are the details of the implementation and nomenclature for those system parts. Separation of Hardware and Software (HW/SW split), separation of signaling and data (control-plane/user-plane split or CP/UP split), individual functions definition and security mechanisms are examples of those.

The most recent advancement present in the industry in this context is the 5G technology, covered by the author of this thesis in **[MD3]** and which is briefly summarized below[3]. The key requirement for the 5G architecture, as already mentioned, is to support the variety of use cases, services and requirements. Additionally, different business models, such as Network-as-a-Service (NaaS), need to be supported. Capabilities needed to achieve this include the possibility to tailor and optimize the network operation for each usage, together with high programmability and scalability. The introduction of Software-Defined Networking (SDN) [9], [10] and Network Functions Virtualization (NFV) [11] enables the shift from specialized hardware-based networks (using network nodes) to programmable software-based architectures (using network functions). The key in this approach is to define a set of network functions that should be interconnected and mapped to different locations (the so-called Points-of-Presence or PoP) for each need, using commodity hardware instead of defining the specialized network elements. The other aspect of 5G is the possibility to reuse the LTE network as per "support for multiple access technologies" requirement [8]. Taking these considerations into account, the following studies are being conducted within the 3GPP: network slicing, RAN flexibility, tight interworking with LTE and novel Quality-of-Service (QoS) framework [12]. The 5G system encapsulates both, the NR and the evolved LTE, connected to the 5G Core Network (5GC). The smooth migration from LTE towards fully fledged 5G is also required and is being worked on within the 3GPP. 5G also considers tight interworking with Wi-Fi, along with similar approaches taken by the LTE (see **Chapter 13 in [MD3]** for details), where LWA,

[3] This paragraph is a reworked version of a paragraph in Chapter 14 in [MD3] © Artech House 2017, used with permission of the publisher.

LWIP, and RCLWI features are supposed to be the baseline for NR-WLAN interworking [12]. In terms of legacy systems, the 5G system is not supposed to consider 2G and 3G in the following aspects: no support for CS voice call continuity or fallback, no support for 2G/3G access to 5GC and no support for seamless handover between those [8].

Another set of building blocks, which is similar across generations (but which differs in terms of details of implementation and individual features from generation to generation), can be drawn on the resource management architecture. The main components include: *low level RRM* (MAC layer algorithms, like Link Adaptation (LA), Power Control (PC), radio resource scheduling etc., operating typically on a short timescale with fast adaptation loop), *high level RRM* (Radio Resource Control (RRC) layer algorithms, like Traffic Steering – TS, Admission Control – AC, Mobility Management – MM, Congestion Control – CC etc., operating typically on a long time scale, with slower adaptation loop), *network management* (wider scope and slow adaptation, like SON algorithms, e.g. Energy Saving Management – ESM, Mobility Load Balancing – MLB, Mobility Robustness Optimization – MRO, Inter-Cell Interference Coordination – ICIC etc.) and *network orchestration* (policies and strategies, e.g. virtual resource scaling, SON coordination, Licensed Shared Access (LSA) management and supporting functions, like REM or Minimization of Drive Tests – MDT).

2.3 Systems complexity overview

The increasing amount of available spectrum resources, equipped with a number of the spectrum access technologies, provides a complicated system to operate, with a complex coordination of the resources, among RAN nodes. Figure 2 presents an example of a HetNet comprising of macro- and SC layers, accompanied by various spectrum access techniques, including CA and DC, and utilizing both the licensed and unlicensed spectrum bands **[MD2]**.

As already mentioned in previous sections, when moving towards the 5G era, different requirements have been posed by vertical services. However, it is worth mentioning that the system is not supposed to always fulfill all of them at once, but rather deal with specific requirements of the specific service, wherever and whenever needed. In other words, different services require different types of optimizations, e.g. eMBB focuses on high throughput and capacity, while mMTC focuses on long battery life and deep coverage, and URLLC on high reliability and low latency **[MD3].**

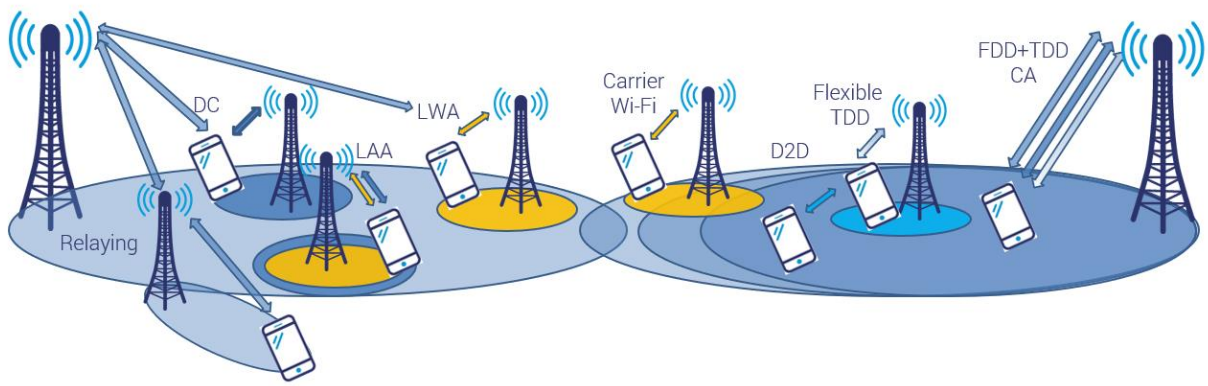

Figure 2. Heterogeneous Network (figure reproduced from [MD2]).

When considering the complexity of mobile systems, along with their evolution, three main points have been identified by the author of this dissertation (as specified in e.g., **[MD10], [MD11]**):

- network densification techniques, new spectrum access schemes and the growing availability of radio access solutions focused towards spectral efficiency improvements are all increasing the flexibility of the RRM scope, which, due to this, yield an increase in its complexity **[MD10]**;
- considering the variety of the envisioned 5G requirements, the RRM scene is highly fragmented and, to fulfil 5G expectations, it is required to provide a unified and scalable approach to radio resources handling **[MD11]**;
- backwards compatibility, which is a typical requirement for most systems, makes the ecosystem complicated. Clean-sheet approach would simplify new systems' design, but it is almost never possible, due to the need of integrating the novel technologies with the legacy ones.

2.4 Approaches to complex networks management

As elaborated in previous sections, with the advent of 5G technology, it became obvious that the network will have to cope with different requirements, accompanied by the envisioned vertical services. The resulting network should be flexible enough to simultaneously support optimized configurations for different services posing the diverging requirements, which may be contradicting to each other **[MD3]**. The author sees three possible ways to handle this requirement (see Figure 3):

- designing separated systems to realize different requirements, i.e. creating fragmentation of the solutions. However, introducing a new system every time when there is a need to meet the requirements of a new application and integrating with the existing systems is very costly;
- designing a single system to meet all the necessary requirements. The drawback of this approach is that it is essential to meet all the requirements in advance and make an over-dimensioned and complex system;
- providing a natively unified and hierarchical approach to the design of the system, with abstraction layer(s) in order to easily introduce new features and meet the requirements not known in advance. The basic assumption in this approach is to design optimized solutions on the lower layer and generic, unified mechanism on top.

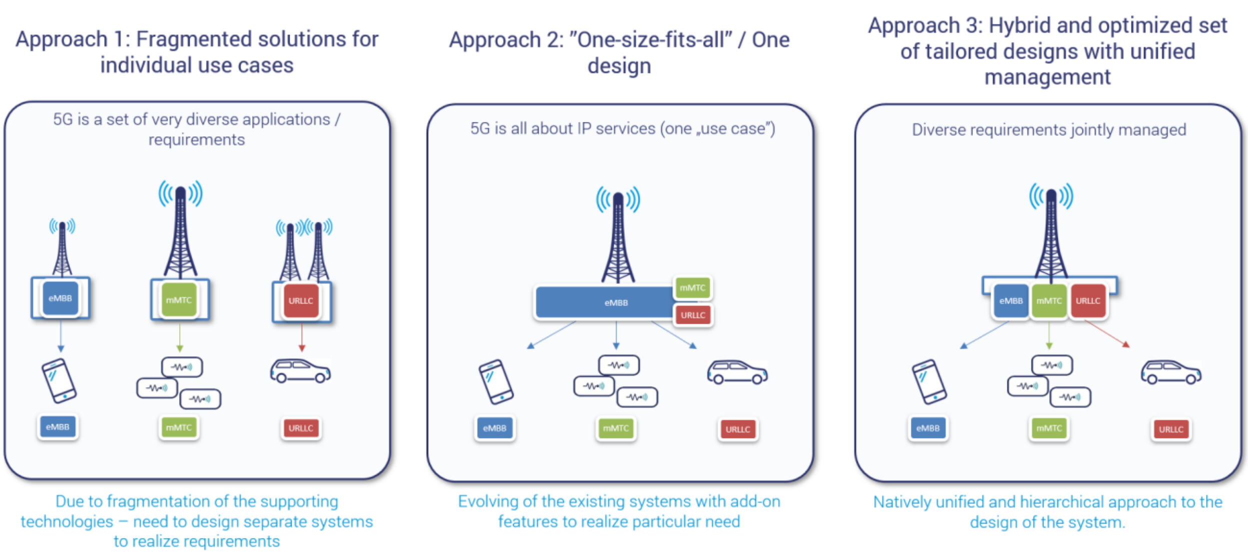

Figure 3. Three design approaches for management of complex networks

Taking the above into account, the previous generations of mobile systems were designed to focus on a single type of service (e.g. voice or Internet access). With the emerging IoT and new vertical markets, as well as with the ever-increasing need for capacity and throughput for broadband access, this legacy approach is no longer going to succeed in 5G **[MD3].** The author of this dissertation proposes to handle the heterogeneity of RATs, spectrum bands and types, devices, service mixes and features by creating a framework in the form of a hybrid mechanism with three main components: a unified upper layer (handling the context independently of the underlying technology), an abstraction middle layer (enabling an "easy" add-on of the techniques below and making the upper layer independent of the specifics of the specialized solutions) and a specialized lower layer (to best serve a particular purpose). Chapter IV of this dissertation discusses this approach in detail.

2.5 Summary of contributions provided in this chapter

The key author's contributions and proposals within this chapter are based on **[MD1]**, **[MD2]** and **[MD3]**:

- providing an overview of the evolution of wireless systems and sketching the HetNet, emphasizing the key aspects, which make the wireless systems complex;
- identifying the main points of complexity in wireless systems;
- providing the scope of possible solutions for management of wireless systems, together with the advantages and disadvantages, and providing the reasoning for the proposed hybrid solution.

Chapter III.

Wireless systems complexity

The recent 3GPP standardization within the RAN group gave clear indications of raising requirements for further improvements of spectrum allocation flexibility, both within the evolved LTE and 5G-NR, including more spectrum resources and novel spectrum access schemes. Different spectrum bands, ranging from 450 MHz up to 100 GHz, covering the licensed, unlicensed and licensed-shared allocations, together with various spectrum access methods and optimization techniques, create a complex spectrum landscape, which, in turn, increases the overall complexity of the RRM in mobile networks **[MD2]**.

This chapter decouples the system's complexity problem by providing an analysis of different aspects and, towards the end, by defining the Spectrum Toolbox to systemize individual elements.

This chapter is based on the author's experience and conclusions gathered from different projects, that resulted in the following publications: **[MD1]**, **[MD2]** and **[MD3]**, and is based on those publications. The goal of this part is to provide detailed description and analysis of different elements of wireless systems, resulting in a landscape that is complicated to manage. This part provides input to the definition of the resource management framework, to be proposed in Chapter IV.

3.1 Features along the way of the LTE evolution[4]

LTE system is continuously developed and enhanced, with more features allowing to improve the system's performance and introduce new services, such as smart metering and vehicular communications, which pose significantly different requirements, as compared to mobile broadband, for which this system was originally designed **[MD3]**.

[4] This section is a reworked version of sections 13, 13.1 and 13.8 in [MD3] © Artech House 2017, used with permission of the publisher.

System's capacity, higher throughputs and connectivity robustness improvements of the LTE-Advanced Pro include the following set of features, as specified in **[MD3]**:

- DC – enables aggregation of two radio links of non-ideal backhaul (i.e. without low-latency requirement). To allow this, links are aggregated at the Packet Data Convergence Protocol (PDCP) level, where the PDCP Packet Data Units (PDUs) are combined, rather than MAC-layer Transport Blocks (TB) aggregation, which is done within CA framework. The links of a single macro-cell and SC are combined in a way, that the macro-cell acts as a mobility and signaling anchor and the SC as capacity booster [13], [14];
- LWA – provides link aggregation, where the secondary link is provided via Carrier Wi-Fi at a 2.4 GHz or 5 GHz Industrial, Scientific, Medical (ISM) band, enabling tight interworking between LTE and WLAN. The point of aggregation is at the PDCP level of the LTE anchor, similar to the DC feature. Release 13 specifies this in the Downlink (DL) direction (i.e. the Wi-Fi link serves as a supplemental DL). Release 14 further enhances this feature with the Uplink (UL) transmission direction under the name of enhanced LWA (eLWA) [14];
- LAA – aggregates the licensed primary LTE carrier with the secondary link using the new LTE radio frame format suited for unlicensed operation and fulfilling the fair-coexistence requirement (to be interoperable with Wi-Fi at the 5-GHz ISM band). Similar to LWA, Rel-13 specifies this feature only for the DL, while Rel-14 proposes enhanced LAA (eLAA), which adds UL support [3];
- Massive CA – extends the regular CA feature towards a larger number of component carriers, including the licensed and unlicensed bands. This feature enables combination of up to 32 CCs, which theoretically provides up to 640 MHz of aggregated bandwidth. Each of the CCs complies with the LTE Rel-8 channel Bandwidths (BW) and supports backward compatibility [14], [15].

On the other end of LTE improvements, there are functionalities relating to IoT-type of services, including: NB-IoT and D2D communications, as discussed in **[MD3]**:

- NB-IoT – a novel system design, in which a new Physical (PHY) layer is defined, along with protocol stack adjustments to work under the legacy LTE framework. The aim is to significantly simplify the system's operation for low-end devices, with decreased system BW to 1 Physical Resource Block (PRB), i.e. 180 kHz, coverage enhancements and reduced feature support for power consumption decrease [14];

- D2D – refers to direct communication between devices under the mobile network's supervision for resource control handling. New transport and physical channels are specified under the SL name. Additionally, vehicular communication further expands this framework within Release 14, using SL for Vehicle-to-Anything (V2X) communications [14].

Table 1. LTE system evolution steps [MD3]

System name	LTE: Rel-8, 9	LTE-Advanced (LTE-A): Rel-10, 11, 12	LTE-A Pro: Rel-13, 14
Main Purpose	Provide high throughput for MBB, prepare mobile system for evolution towards 4G	Fulfill IMT-Advanced requirements for 4G system	Mark evolution point with significant improvements to the LTE-Advanced
Key features	OFDMA, DL MIMO (4x4), Modulation with up to 64QAM, Flat architecture (eNB), Flexible system BW	CA (extending system BW to 100 MHz), Enhanced DL MIMO (8x8), UL MIMO (4x4), Small Cells, HetNet, eICIC, SON, CoMP, ePDCCH	DC, LAA, LWA, Modulation 256QAM, EB/FD-MIMO, D2D, V2X, NB-IoT, eMTC
Max system BW and DL Modulation	20 MHz / 64 QAM	100 MHz / 64 QAM	640 MHz / 256 QAM
Number of DL spatial layers	4	8	8
Max DL spectral efficiency	15 bps/Hz	30 bps/Hz	40 bps/Hz
Max DL throughput	300 Mbps	3 Gbps	25.6 Gbps

The table is a reworked version of two tables from [MD3]. The full tables can be found therein.

To sum up, from the initial LTE system design, released in 2009, significant improvements have been made through the evolutionary steps within 3GPP, until recent. LTE Rel-8 was a pre-4G system, later accompanied with a set of features to fulfill the 4G requirements of IMT-Advanced. Currently, it is still being developed to go beyond 4G, and is also assumed to be a part of the 5G framework to be submitted as a Radio Interface Technology (RIT) to ITU-R, along with NR. Table 1 provides high-level comparison of key evolution steps of the LTE system, based on **[MD3]**. The detailed description of the features, along with practical implications on the system and the performance calculations made by the author of this dissertation, are provided in **Chapter 13 of [MD3]** while the comparison of different LTE features, including the advantages and disadvantages, is provided in **[MD2]** and **[MD10]**.

3.2 Spectrum, channel bandwidths and spectrum licensing methods[5]

General spectrum bands for E-UTRA are outlined below (according to [16]):

- FDD [GHz]: 0.45, 0.7, 0.8, 0.9, 1.5, 1.8, 1.9, 2.1, 2.3, 2.6, 3.5;
- TDD [GHz]: 0.7, 1.8, 1.9, 2.0, 2.6, 2.3-2.4, 2.5-2.7, 3.4-3.8;

while the detailed arrangement is presented in **[MD2]** including different duplex modes, depicting Supplemental DL (SDL) carriers and highlighting bands with the reversed DL/UL channels arrangement. In the case of spectrum bands for the IEEE 802.11 technologies, unlicensed frequency bands are the following (according to [17]):

- IEEE 802.11b/g/n/ac/ax [GHz]: 2.4, 5;
- IEEE 802.11ax [GHz]: 6;
- IEEE 802.11ad [GHz]: 60.

Currently, LTE covers spectrum bands up to 4 GHz, while Wi-Fi is already standardized to operate within the unlicensed part of the millimeter Wave (mmWave) spectrum, e.g. 60 GHz band within the scope of IEEE 802.11ad. 5G is expected to bring operation within much wider range of spectrum bands, covering frequencies up to 100 GHz in both the licensed and unlicensed variants **[MD2]**. The frequency ranges for the 5G-NR phase I (3GPP Rel-15) include up to 6 GHz band (the so-called Frequency Range 1 – FR1) and up to 52.6 GHz (above 24 GHz called the Frequency Range 2 – FR2) [18], [19].

In terms of channel BWs, the baseline LTE standard (i.e. 3GPP Rel-8) was defined as a system based on Orthogonal Frequency Division Multiple Access (OFDMA) supporting a single carrier with various predefined values, i.e. 1.4, 3, 5, 10, 15, 20 [MHz]. As an interesting development, 3GPP Rel-14 study on the LTE bandwidth flexibility was agreed [20], with the aim to investigate further enhancements of the channel allocation flexibility, in order to improve the spectrum utilization. This was specifically dedicated

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[5] This section is a reworked version of different sections in [MD2] Copyright © 2017 M. Szydelko and M. Dryjanski, licensed by EAI. This is an open access article distributed under the terms of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/3.0/), which permits unlimited use, distribution and reproduction in any medium, as long as the original work is properly cited.

to be applied in regions, where non-Rel-8 compliant spectrum blocks are available for operators (some examples here are e.g. 1.8, 2.2, 4.4, 6, 6.2, 7.8, 8.0, 14, 19 [MHz]) **[MD2]**. Going further, specifications for 5G-NR define the channel bandwidths in the following range: 5 – 400 MHz, depending on the frequency range [18], [19].

Rel-10 LTE-Advanced introduced a CA feature to aggregate multiple CC with the use of MAC layer scheduling to go beyond single carrier used by LTE Rel-8. Initially, CA allowed to use up to 5CC, where each individual CC is reusing any of the Rel-8 BW size for backwards compatibility purposes. The theoretical maximum aggregated spectrum bandwidth summed up to 100 MHz with intra-band consecutive, non-consecutive or inter-band CA options. Different component carriers' allocation for the UL and DL could be used to reflect the expected traffic demand by use of non-symmetrical configurations (e.g. 3DL CC, 1UL CC). In this context, it is important to mention the concepts of the Primary Cell (PCell) and Secondary Cell (SCell), where the former is used for signaling and user data purposes, while the latter only serves the data to increase the user's throughput. In further releases, more flexibility in terms of the spectrum arrangement was allowed by joint aggregation of Time Division Duplex (TDD) and Frequency Division Duplex (FDD)-based Component-Carriers mixing. Rel-13 extended the spectrum aggregation mechanisms towards a higher number of aggregated bands and towards the use of unlicensed spectrum for mobile networking with Massive CA, which enabled to use up to 32CCs. This theoretically provides up to 640 MHz of aggregated bandwidth, while still fulfilling backwards compatibility with the LTE Rel-8 channel BWs **[MD1], [MD2]**.

Licensed spectrum allocation per Mobile Network Operator (MNO) is the basic principle for the mobile network's operation, requiring acquisition of the spectrum license. Unlicensed spectrum usage by MNOs was already considered in 3GPP Rel-8 for traffic offload. In this context, the 3GPP has introduced LAA, an unlicensed spectrum access scheme with a version of LTE air interface tailored to ISM bands characteristics. Additionally, ISM spectrum usage was considered under the LWA or RCLWI schemes with Wi-Fi as the secondary RAT. The third option is proposing a shared scheme for 2.3-2.4 GHz band, called the License Shared Access (LSA or Authorized Shared Access, ASA) [21]. LSA allows spectrum owners (also known as Incumbents) to share their licensed radio resources with other market players (also known as LSA Licensees) **[MD2]**.

From this aspect alone, it can be concluded that different options for channel BW, spectrum range and licensing schemes are creating significant difficulties to manage the system resources, in particular, where combining LTE, 5G-NR and Wi-Fi in the upcoming RAN configurations. More details on the individual aspects presented above can be found in **[MD1]** and **[MD2]**.

3.3 Radio access technologies and network layers

The recent RAN can be composed of different network layers of one technology (e.g. LTE macro-layer, together with LTE SC layer), along with different radio access technologies (e.g. LTE, NR, Wi-Fi, LTE-LAA, NB-IoT), not even mentioning the older technologies, like 2G or 3G. Additionally, different communication schemes can be used, like direct communication (with the use of D2D) or relaying schemes. Another perspective to look onto the network layers is by splitting the RAN into the *coverage layer* (typically a macro-site providing wide coverage) and *capacity layer(s),* provided either by SCs, using a different carrier, or by another CC (typically of higher frequency) used by the same macro-sites. Figure 2 in Chapter II shows an example of how the resulting RAN can look like when using those items together, creating a complicated version of the network, called the HetNet.

One of the main features to capture, when speaking of the HetNet evolution, is in the area of spectrum aggregation management, which is through the aggregation of different carriers using DC. In DC, the spectrum is aggregated in an inter-site scenario, where a macro-cell serves as a mobility anchor (being the so-called Primary Cell Group, PCG, also known as Master Cell Group, MCG) whereas the additional radio link provided by the Small-Cell (providing the Secondary Cell Group, SCG) allows local capacity boosting. DC facilitates CP/UP-split to reduce the signaling overhead and the number of handovers, and, at the same time, improve the end-user's performance. In this scheme, the UP links are split among the available SCs, whereas the user's context (CP) is maintained by the overlay macro-cell (and is moved between macro-cells via regular handover). Additionally, the DC scheme uses the concept of Split Bearer, where, instead of aggregating MAC layer transport blocks (like in CA), the PDCP PDUs are combined, omitting the requirement for low latency and allowing non-ideal backhaul for SC connectivity **[MD2]**. Other features, fitting onto the HetNet scenario, include LAA, LWA and the evolution of DC, which appeared with the introduction of NG-RAN and NR in the context of 5G, namely the Multi-RAT Dual Connectivity (MR-DC). MR-DC allows to support different scenarios, depending on which RAT provides the MCG and which provides the SCG, in the tight interworking configurations between LTE and NR [22].

An example of practical configuration is provided in **[MD10],** where the considered scenario for HetNet in a Dense Urban (DU) area consists of multi-band (several CCs) macro-layer and SC-layer, including various RATs (i.e. LTE-FDD, LTE-TDD, LTE-LAA and Wi-Fi). In contrast, another HetNet configuration within a Suburban (SUB) area is provided, where the users are served by a multi-band macro-layer only, but with the use of Advanced-Antenna Systems (AAS) for densification purposes. Both of those scenarios require radio resource coordination on multiple levels: inter-RAT, inter-band, inter-site, inter-layer and a combination of those two when being adjacent to each other is also a HetNet.

The contribution of the author of this thesis in the area of HetNet, in combination with CA, focusing on CA management (including low level RRM, namely the CC scheduling, and upper level RRM, namely the CC configuration) can be found in the author's supplementary material **[MD3supp]**.

3.4 SON features coordination

Automated network management has already been discussed for a decade within the scope of LTE, since its beginnings, under the term Self-Organizing Networks (SON). The idea is to automatically enhance the network's operation by adapting configuration and parameter settings based on system's and devices' measurements for optimization purposes. Within the context of 3GPP, SON is split into three main phases of network operations – Self-Planning and Configuration, Self-Optimization and Self-Healing. The key features are: Mobility Load Balancing (MLB), Mobility Robustness Optimization (MRO), Automated Neighbor Relationship (ANR), Coverage and Capacity Optimization (CCO), RACH Optimization (RO), Inter-Cell Interference Coordination (ICIC), Cell Outage Compensation (COC) and Energy Saving Management (ESM) [23].

The SON concept and individual SON features were already studied in 2010 within the FP7 SOCRATES project [24], where it became obvious that SON features can invoke contradicting actions, thus the need for coordination arised. This evolved into a consecutive project, FP7 SEMAFOUR [25], focusing on providing the generic network management and coordination mechanism for the SON features in the HetNet scenario. The SON coordination framework is also present within the 3GPP scope and can be found in [26].

Examples of coordination needs were also addressed by the author of this dissertation, within **[MD10]**, **[MD11]**, being the foundation to provide the concept of Unified Traffic Steering framework (more details on this concept is provided in Chapter V of this dissertation), and are briefly discussed in this paragraph for exemplary purposes. There could be conflicts among SON features when operating in the same area on the same sites. For example, MLB vs. MRO may have contradicting impact on the Cell Individual Offset (CIO) updates, due to different function goals (e.g. MLB may want to move the traffic towards one cell, due to load imbalance, while, at the same time, MRO may trigger an opposite action due to mobility performance issues, like handover failure rate). In a different example, MLB and CA-reconfiguration may be both invoked when cell load exceeds certain threshold level, thus those two features require proper prioritization, as it might not be required to use both of them at certain cell load conditions to decrease overload. In yet another case, MLB and Multi-carrier load distribution features the needs to be adjusted together, since they aim to achieve the same goal, but for CONNECTED and IDLE mode respectively. Yet another example shows that the ANR and Physical Cell Identifier (PCI) adjustment has to be updated together to properly set the neighboring relations **[MD11]**.

3.5 Multitude of traffic types, along with 5G introduction[6]

The variety of services proposed for 5G brings diverging requirements, ranging from high-end services (namely, eMBB), through extremely low latency communication (namely URLLC), down to low-end MTC (namely mMTC) applications with very sporadic transmissions using several bytes. To support different connectivity requirements (resulting from a wide range of services) within a single block of spectrum, the system should be very flexible [27]. However, it is not obliged to fulfill all of requirements of different services

[6] This section is a reworked version of section 14.2 in [MD3] © Artech House 2017, used with permission of the publisher.

at the same time, but rather fulfill specific requirements of a specific service wherever and whenever required. An overview of the three main use cases' requirements is presented below **[MD3]**:

- eMBB requires very high throughput and high capacity, as well as support for mobility, that varies from a very stationary application to very high mobile applications;
- mMTC, in turn, requires very low throughput; thus, the connection efficiency is very important (namely the reduction of the signaling-to-data ratio). It is also important to assure high coverage to get deep into basements, reducing battery consumption and minimal mobility support, as mMTC is typically used for services in which the UEs are stationary (e.g. sensors);
- URLLC requirements are on the other extreme, where very low latency (or, in some cases, predictable latency and low jitter) plays crucial role. Reliability is another aspect of these types of services that require very high probability of small packet delivery in short time. Along with reliability, in mobility scenarios, the interruption time should be very low, coming down to 0 ms (which effectively means no interruption time). This requires a make-before-break cell change type, where the source connection is released only after the new one is established, so that the packets can be delivered to the network without any time loss.

The other aspect in this context is that the traffic density (or area capacity) can be high in both the eMBB and mMTC scenarios. However, it is due to different reasons, namely in eMBB, where each user generates significant amount of traffic, whereas in mMTC there is a significant number of devices transmitting very low amount of traffic. Thus, the aggregated throughputs can be significant, while the individual link characteristics are very different, requiring different optimizations on the network side **[MD3]**.

More details of the specific services can be found in **Section 14.2 in [MD3]**, while the key requirements, imposed on the system coming from these different vertical services, are gathered in **Table 14.2 in [MD3]**.

3.6 Spectrum Toolbox

To summarize the considerations from previous sections, this one gathers and systemizes the available frequency bands, spectrum aggregation mechanisms, spectrum licensing and duplexing schemes, spectrum sharing schemes and spectrum refarming techniques. This is done under the name “Spectrum Toolbox”, which is proposed and discussed in details within the two articles: **[MD1]** and **[MD2]** (to the definition of which the author of this dissertation has contributed). The investigated Spectrum Toolbox evolution across 3GPP releases is shown in Table 2.

Table 2. Spectrum toolbox evolution across LTE releases [MD1]

3GPP release	**LTE: Rel-8, 9**	**LTE-A: Rel-10, 11, 12**	**LTE-A Pro: Rel-13, 14**	**5G phase I: Rel-15 5G phase II: Rel-16**
Frequency bands [GHz]	0.7, 0.8, 1.8, 2.1, 2.3-2.4, 2.5-2.6GHz	0.45, Digital Dividend, 1.5, 3.4-3.8GHz	5GHz ISM; WRC-15 bands	New bands below 6GHz for 5G NR, mmWave
Spectrum aggregation	Single Carrier symmetric DL/UL	Dual Connectivity, Carrier Aggregation	Massive CA (up to 32CC), LAA, LWA, SDL	Multi-Connectivity, SDL for CA, SUL Lean carrier (NR)
Spectrum licensing schemes	Licensed spectrum only	Licensed, Carrier Wi-Fi	Licensed, Unlicensed, (LAA, LWA) LSA	Co-existence of: exclusive licensed, shared license-exempt spectrum, enhanced LAA
Duplexing schemes	Separate FDD, TDD	Combined FDD and TDD, eIMTA	FDD, Flexible Duplex	Flexible TDD
Sharing schemes	Static schemes (MOCN, MORAN)	Static schemes (MOCN, MORAN)	RSE, LSA	LSA, CBRS, spectrum trading
Spectrum refarming	Static	Static	Dynamic, DSA, MRAT Joint Coordination	Dynamic, opportunistic

The table is a reworked version of a table from [MD1]. The full table can be found therein. The proper references to each individual element in the table are provided in [MD1].

To provide a qualitative comparison of the proposed Spectrum Toolbox’s elements, the analysis of their advantages and disadvantages is provided in Table 3 (the detailed analysis of the individual features is provided in **[MD2]** and **[MD10]**).

Table 3. Advantages and disadvantages of Spectrum Toolbox features [MD2].

Feature name	Advantages	Disadvantages
Carrier Aggregation (including Massive CA)	• Improves user throughput and cell capacity • Possibility to aggregate different spectrum bands and MAC layer management • Extension beyond single carrier allocation • Enables to acquire multitude of bands and BWs to increase capacity and mix licensed with unlicensed bands	• Not possible to aggregate spectrum in non-ideal backhaul RRH deployments • Scheduler complexity (CA and non-CA users) • Multiple market-specific CA band combinations • Complexity of RF chains
Supplemental Downlink	• Possibility to adapt aggregated capacity to the required DL/UL demand • Aggregation and management on MAC	• Feature limited by the available SDL-specific bands • CA-based operation only
Dual Connectivity	• Adds spectrum aggregation opportunity for non-ideal backhaul inter-site • Enables CP / UP split • Extension to aggregate multi-RAT aggregation on PDCP level	• Not possible to allocate resources on MAC level • May have problems at anchor cell boundary due to both Macro and SC change • Requires an additional scheduler
LTE-WLAN Aggregation	• Enables to aggregate multiple-RATs • Use of free unlicensed spectrum • Enables use of widely available technology • Most terminals support Wi-Fi already	• Requires carrier Wi-Fi access nodes deployment • Requires additional scheduler at PDCP level • Doesn't support interference management in ISM bands
License Assisted Access	• Use of free unlicensed spectrum • Most terminals support Wi-Fi bands already	• No support for interference management (ISM) • Lower spectral efficiency than in licensed bands • Additional radio interface at UE and RAN side
Dynamic Spectrum Access	• Enable on-demand spectrum refarming • Possibility to adjust capacity to actual demand in a dynamical manner • Limits guard-band gaps that are imposed by static refarming	• Gains limited by the amount of the legacy spectrum to be refarmed (i.e. 2G and/or 3G)
FDD	• Easier resources management due to decoupled DL and UL (separate schedulers) • Interference management less complex than TDD	• In case of non-symmetrical DL/UL traffic, non-optimal spectrum resources allocation
Static TDD	• Improves spectral efficiency in case of non-symmetrical traffic between DL/UL • Channel reciprocity for channel estimation	• Not possible to dynamically adapt DL/UL share to traffic demand • Requires inter-site coordination for interference avoidance
eIMTA	• Enables dynamic on-demand UL/DL adaptation of resources allocation • Boosts TDD advantages	• Requires isolation between cells for DL/UL interference avoidance • Requires proper site coordination in case when SCs are not isolated • Application to high frequency bands (due to cell isolation requirement)
Sub-6GHz spectrum	• Wide area access (lower bands) • NLOS operation possible • Good for high mobility (lower bands)	• Limited availability (most bands highly occupied) • Fragmented spectrum chunks (lack of large contiguous spectrum blocks)
mmWave spectrum	• Large contiguous spectrum chunks • Enables use of Massive MIMO due to small antenna elements sizes	• Short range only (depending on scenario) • Severe blocking effects • New channel models required
Licensed Shared Access	• Possibility to use licensed spectrum on a shared manner with other licensees • Possibility to adapt the required capacity to traffic demand on a per-Tx basis	• Limited to certain bands • Semi-dynamic, not possible to adapt spectrum availability in a highly dynamic manner in case of fast changes of traffic within Small Cell

The table is a reworked version of a table from [MD2]. The full table can be found therein. The proper references to each individual feature in the table are provided in [MD2].

The key observations resulting from the analysis provided in this chapter are as follows:

- considering the above solutions and the standardization of 5G, the presented Spectrum Toolbox is expected to further evolve over time and the new technology elements will be added. Thus, the Spectrum Toolbox will become more complex, but will also provide more flexibility in spectrum allocation. Because of that, the Spectrum Toolbox will have to be managed in adaptive and automated way, evolving towards cognitive mechanisms, equipped with self-learning and self-optimizing solutions **[MD2]**;
- there are certain features and spectrum bands which have different advantages and disadvantages, which make them suited for different applications or use cases, and it is required to use combination of them to fulfill the requirements of those applications or use cases in a unified manner.

From the above discussion, the author concludes that there is a need to provide a scheme to manage those functionalities in an efficient manner, in order to minimize the complexity of adding new features, bands, access methods, transmission schemes into the overall system, and, in turn, to decrease the need to redesign the system in order to support them.

3.7 Summary of contributions provided in this chapter

The key author's contributions and proposals within this chapter are based on **[MD1]**, **[MD2]** and **[MD3]**:

- providing a detailed analysis of the individual elements for complicated HetNet, which requires a unified management framework;
- providing the definition of Spectrum Toolbox as a classification mechanism for simplified analysis of new features in order to serve as an input to the design of the unified resource management framework.

Chapter IV.

Design of resource management framework

This chapter is based on the author's experience and conclusions gathered from different projects, that resulted in the following publications (grouped by subject):

- **Hierarchization, specialization and optimization, independency and abstraction layer** (based on Unified MAC layer design work)**: [MD4] - [MD9]** (the detailed work done by the author, which resulted in those publications, is provided in the supplementary material, namely: **[MD1supp], [MD2supp]**);
- **Unification and flexibility** (based on work on the Unified Traffic Steering framework)**: [MD10]**, **[MD11]**;
- **Hierarchization** (based on Unified MAC layer design and REM work)**: [MD5]**, **[MD7]**, **[MD8]**, **[MD9], [MD12]**, **[MD13]**, supplemented by the detailed analysis in: **[MD1supp], [MD2supp]**);

Summarizing the discussion in Chapter II and III (and the details of those, provided in respective publications) on network complexity, the current network landscape consists of *different*:

- network layers – macro-cell layer, small-cell layer;
- cooperating technologies/RATs – LTE, NR, Wi-Fi, NB-IoT, eMTC;
- communication schemes – device-to-device communication, relayed communication, UE-to-network communication;
- spectrum licensing schemes – licensed, unlicensed, license-shared;
- UE capabilities – CA-capable, DC-capable, NB-IoT-only, UE category, NR support;
- spectrum bands – sub-6GHz and above 6 GHz, with multitude of configurations;
- duplexing schemes – FDD, TDD, dynamic TDD;
- spectrum aggregation/cell aggregation schemes – CA, DC, LAA, LWA, MR-DC (LTE and NR DC in different scenarios / tight interworking);

- resource management features – low-level RRM (MAC layer scheduling, CA scheduling and interference management), high-level RRM (AC, CC, TS, MM, PDCP scheduler), SON features (MRO, MLB, ESM, CCO, ICIC, COC);
- traffic demand – local high-capacity hotspots, low-capacity wide areas and traffic patterns, changing daily and weekly;
- operator strategies – energy minimization, offload traffic, performance maximization, best effort service provisioning, QoS assurance;
- services and use cases – eMBB, URLLC, mMTC, voice and subsets of those.

A major observation from the projects, in which the author participated (namely the FP7 5GNOW project, UTS project, REM project, Spectrum Toolbox project and writing a book), which triggered most of the other conclusions, is *the fact that, when there is an already defined system, tailored for a specific service, and there is a requirement to use this system for a new service, which this system was not designed for, there is a limited number of optimizations that can be done in order to support this service, and thus this approach is not optimal*. Two examples explored by the author of this dissertation to support the above statement are provided below:

- work to support the MTC traffic (work done within 5GNOW project) **[MD4],** where the author was trying to optimize and select the parameters from the LTE system to tailor LTE to the requirement on the battery life and low amount of data that the MTC devices are transmitting, and the UL focused traffic. There was a need to decrease the amount of overhead, which was significant when considering the typical random-access procedure to send very low amount of data. The parameters were selected from whatever baseline the LTE standard allowed to, in order to minimize the overhead and to decrease the number of message exchange between the device and the RAN. During the process, it became obvious that some of the overhead cannot be minimized, while, at the same time, it does not give any reason to be in place – e.g. the "always-on" reference signals or system information. The details of this analysis and the specific settings are described in author's supplementary material, **[MD1supp] Chapter 2**;

- NB-IoT implementation analysis, in order to incorporate it into the LTE framework. The resulted standardized NB-IoT system required certain configurations and optimizations of the air interface (to fit into the LTE framework and due to compatibility reasons) and on the protocol layer (e.g. data transmission over NAS or data transmission over UP, with simplified version of the protocol stack, through switching-off some protocol configurations). Details of this analysis are provided in **[MD3] Chapter 13**.

The author concludes that, by taking the above into account, and in order to make an efficient use of different features and services, new spectrum licensing schemes and considering various scenarios, including the ones which are evolving towards Ultra Dense Networks (UDN), the radio resources coordination shall be addressed on multiple levels, namely the inter-MNO, inter-RAT, inter-site, inter-layer and inter-band level. The overall design of future networks should natively incorporate automated engines (SON-based) to manage the network towards a unified user experience, provided across multiple converged radio access technologies. Additionally, the non-uniform traffic demand, coming from HetNet scenarios, is evolving towards even more complex cases, along with the introduction of new service types, like vehicular communication or IoT applications. To cope with such variable mobile data demands in future networks, it is claimed in **[MD10]** that the access node capabilities, their locations and the resulting density should also be deployed in a non-uniform manner.

The purpose of this chapter is to define a unified approach in order to tackle the complexity of RRM within the current and evolving mobile systems, proposed as an enabler for the spectrally-efficient future mobile networks **[MD2]**. The thesis of this dissertation can be summed up to the statement that *multiple features and technologies should be optimized for the specific requirements and should be coordinated by higher layer*.

4.1 Hierarchization

Hierarchy of the radio resource management and orchestration enable the creation of independency of the unified upper layer from the lower layer tailored solutions.

The examples in 5G context include HW/SW split, CP/UP split, SON over RRM, separate RAN and CN evolutions. The basic idea of the hierarchy in resource management is the following (based on author's contributions in **[MD1supp]** and **[MD2supp]**): firstly, select traffic types that need to be served (or spectrum licensing schemes or radio technologies to be used) and then select proper resource management algorithms (e.g. individual schedulers) and let them operate (see Figure 4).

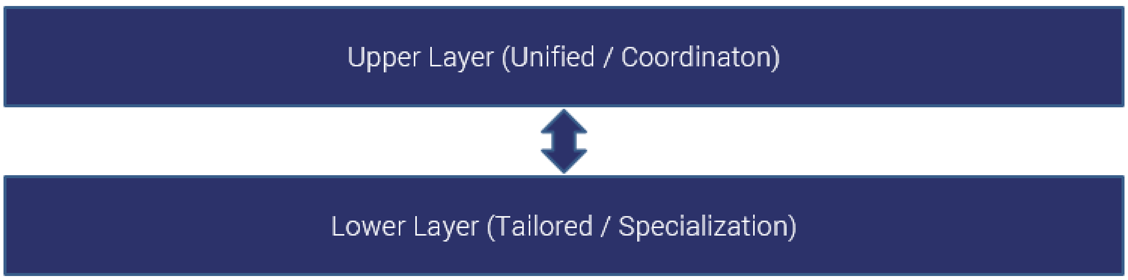

Figure 4. Resource management framework - hierarchy

This approach allows to adjust the policies and operation according to the current traffic situation (e.g. large MTC traffic during a specific part of the day or large data download sessions in the evening in specific places). It allows to define the architecture, where there is a general MAC scheduler, serving as a coordinator of individual "lower layer schedulers", and this, in turn, enables to design or select a proper and optimal solution for particular need, while the generic and unified mechanism takes care of proper communication between internal schedulers **[MD2supp]**.

One example for this approach, proposed by the author of this dissertation, is provided in **[MD1supp]** and **[MD2supp]**, namely the hierarchical MAC architecture (the respective articles are the following: **[MD5]**, **[MD7]** and **[MD8]**).

Another example of hierarchization is provided in **[MD12]**, **[MD13]**where the REMs (or generalized RSMs) are using the scheme to separate the individual aspects from the general aspects. For instance, the specifics of a particular radio interface, or information dedicated to a specific operator (or different timescale of filtering the received information, depending on which RRM level is using it) are separated from the common aspects, like traffic behavior (or common set of information used by all cooperating operators).

4.2 Modularization, specialization and optimization

In the context of variety of different aspects in complex systems, the specialization and optimization refer to a lower level algorithm or function, which is tailored to service, traffic type, feature, spectrum type etc. (see Figure 5).

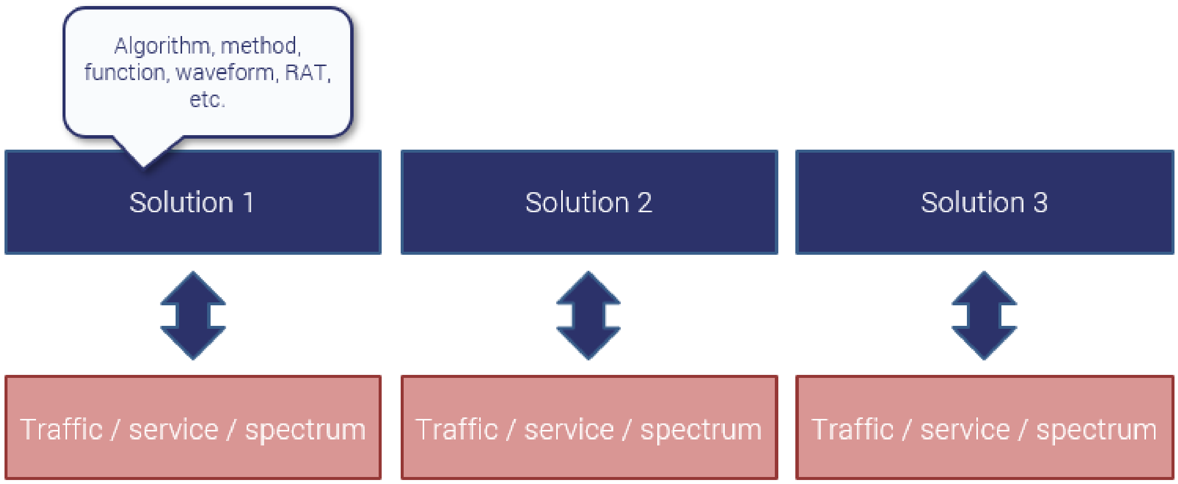

Figure 5. Resource management framework – specialization

Examples, with which the author worked during the 5GNOW project, are Data Physical Random-Access Channel (D-PRACH) concept, Autonomous Timing Advance (ATA) and various non-orthogonal waveforms. The respective publications are **[MD5]**, **[MD6]**, **[MD7]**, and the details of those items can be found in **[MD1supp]** and **[MD2supp]** (more elaboration on the author's work related to those aspects is discussed in Chapter V of this dissertation). Examples of the specific use cases, showing the benefits of this approach, are:

- several waveform approaches, such as Universal Filtered Multicarrier (UFMC), Filter-Bank Multicarrier (FBMC), Bi-orthogonal Frequency Division Multiplexing (BFDM), and Generalized Frequency Division Multiplexing (GFDM) — all of them exposing certain and disruptive advantages over Orthogonal Frequency Division Multiplexing (OFDM) — are put in exemplary scenarios, such as service differentiation, spectrum agility, Coordinated Multipoint (CoMP) Transmission/Reception and real-time transmission **[MD7]**;
- a specific D-PRACH access scheme, using a sparse signal processing concept to efficiently deal with sporadic traffic and control signaling problem for MTC traffic.

Using this scheme, MTC traffic would be removed from standard uplink data pipes, thus drastically reducing signaling overhead, improving operational capabilities and network performance, and improving user experience and lifetime of autonomous MTC nodes **[MD8]**.

Using such approach allows to create a hybrid architecture, which is defined by the author as: *an application of well-defined resource management mechanisms, targeted to specific or individual traffic type or application scenario. This allows to use optimized algorithms to fulfill traffic types' requirements and specifics, and encapsulate them without the need to expose their specifics to the upper layer* **[MD2supp]**.

4.3 Independency and abstraction layer

The abstraction layer enables a straight forward addition of new elements and enables to simplify the upper layer of the hierarchical mechanism, which does not have to know all the specifics (see Figure 6).

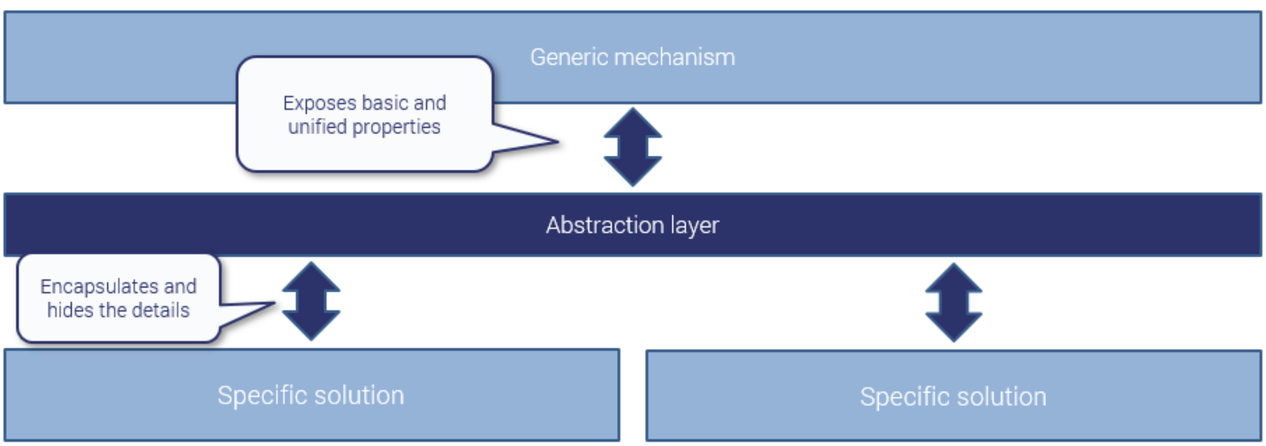

Figure 6. Resource management framework – abstraction

An example, in this context, is the use of system level simulations, where the PHY layer, including all signal processing, cannot be explicitly simulated due to significant complexity. For this reason, typically the PHY layer abstractions for the new waveforms are needed (and used), which must have sophisticated accuracy to capture all the essential characteristics of the PHY layer processes, while, at the same time, not exposing those specifics to the MAC layer (this problem has been addressed by the author in **[MD6]**). Typically, the link-to-system interface comprising of a suitable PHY layer abstraction is used to hide all the details of a particular channel coding, modulation, power control, signal processing etc., allowing the upper layer functionalities (like scheduling, interference handling and mobility handling) to focus on their important tasks. The requirement put on PHY layer abstraction is to use simplified metrics (e.g. Block Error Rate (BLER) vs. Signal-to-Interference-and-Noise-Ratio (SINR) implemented as a lookup table) without the need to actually carry out the real signal processing **[MD6].**

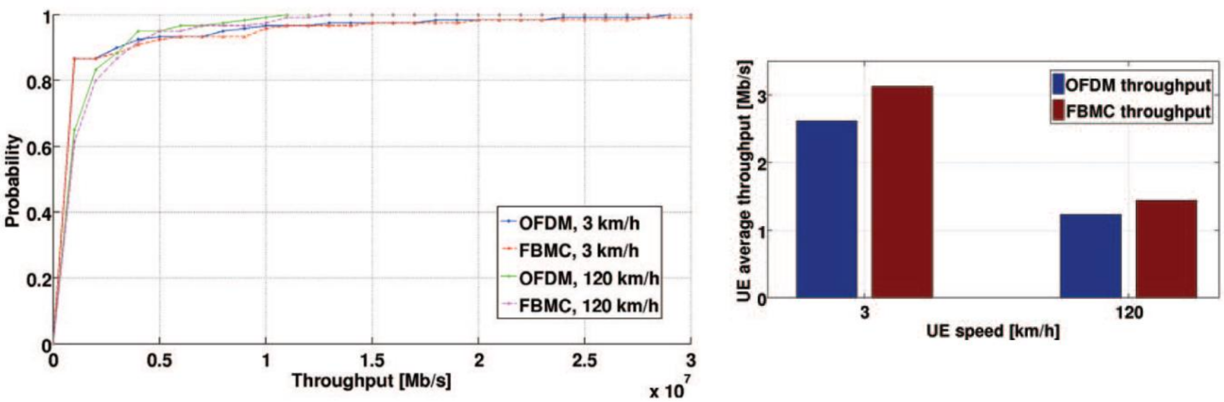

Figure 7. Throughput comparison of different waveforms

(simulations conducted by author in [MD6]. Copyright © 2013, IEEE)

The idea is to create an abstraction below, e.g. MAC layer, where "any" PHY layer can be implemented. In this design, the MAC layer is not aware of the specifics, but is only given certain parameters to manipulate with and "know" which waveform or algorithm to use based on higher level policies or learning from the obtained KPIs. In this particular example, the abstraction is provided via the model of non-orthogonal waveform based on specific SINR calculation, taking into account the specifics of this particular waveform. The MAC layer implementation and the scheduler is independent on the lower level PHY layer implementation. MAC is only aware of "what" use case or traffic type it is suitable for; what are the high-level parameters it can decide to use; what are the metrics to measure the performance. As an example, the simulation results presented in **[MD6]** show that a particular waveform is suitable for a certain scenario – due to less impact from the frequency offset on the performance – FBMC has proven better at higher speeds (see Figure 7). This could give an indication to the MAC layer to use this waveform for this particular application, without the need to modify the whole framework and scheduler implementation.

Abstraction layer in the context of RRM is also presented in [28], where the different schemes for specific air interfaces (5G and Wi-Fi) are used under the same overlay mechanism.

4.4 Unification and flexibility

Based on the work in **[MD10]** and **[MD11]** the conclusion was that it is possible to unify the operation of the various individual RRM features, utilizing the same RRC procedures to be invoked when the action is to be taken. Individual functions (e.g. SON function MRO) invoke certain actions, based on the same or different measures, which, in turn, trigger the lower level procedures (i.e. X2 or RRC). By creating a unified view on this, it is possible to provide a consistent operation, independent of the scenarios, available functions or traffic patterns. Different examples of this are provided in **[MD10]**. In the UTS framework, the intermediate layer, being the unified function, allows to use multiple higher-level algorithms, managing the lower level functions' triggering.

This independency, provided by unification, is an elegant way to incorporate new functions, not known at the time when the framework is created – and thus provides flexibility. To be more specific, new features (e.g. SON/RRM algorithm) or new managed objects (e.g. frequency bands) or new service types, are provided with a unified procedure, allowing them to be added to the framework (a common platform). What needs to be done is to define what are the inputs and outputs (i.e. measures and actions), where does the item belong to (RRM-low level, RRM-high level, SON, radio interface etc.), how does it interact with other functions and what scenario does it fit in (e.g. enhanced ICIC (eICIC) function works only in the HetNet scenario with SCs available). The details of the author's respective research can be found in **[MD10]**, **[MD11]**.

4.5 The unified and hierarchical framework

Based on the design assumptions and individual principles, presented in previous sections of this chapter, the proposed novel generic framework is presented in Figure 8. It covers three layers and is generalized based on the above assumptions – with unified upper layer (context-aware), abstraction middle layer (encapsulating the lower layer solutions) and specialized lower layer (a specialized mechanisms tailored to specific need).

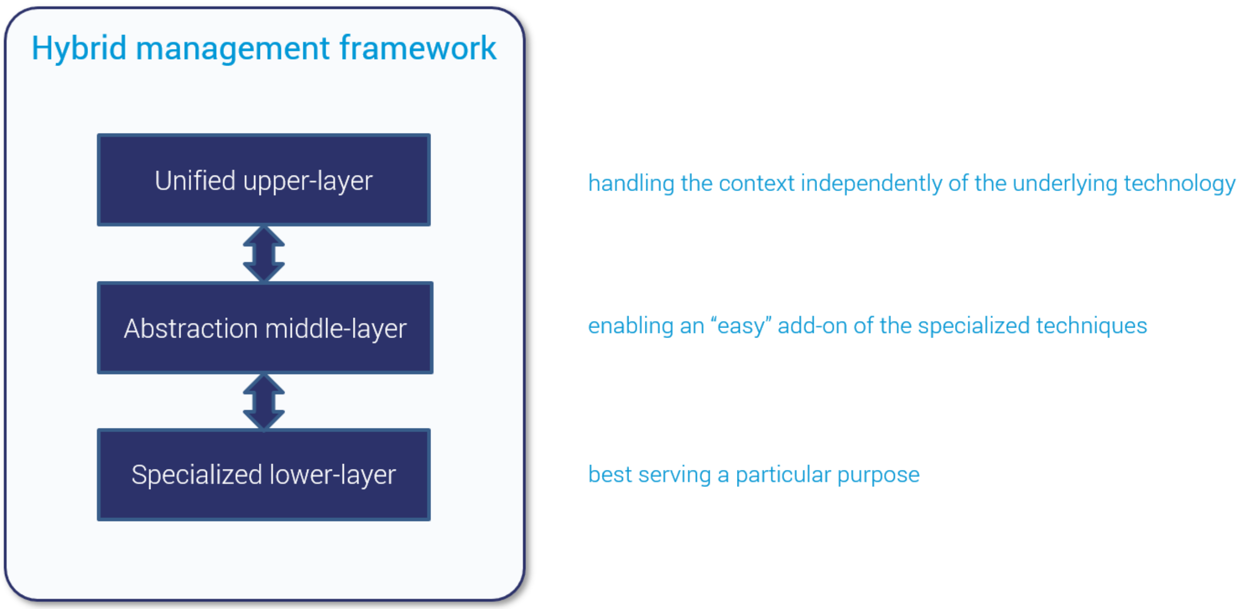

Figure 8. Unified and hierarchical framework – hybrid design

More detailed description of the proposed generic framework is presented in Figure 9. The unified management layer is "context or service aware", and is able to select the lower layer aspects (e.g. the amount of resources, prioritization of an algorithm or function) based on the requirements and feedback. The abstraction layer is needed to translate the upper layer high level parameters to the lower layer specialized algorithms. Those optimized solutions, laying in the bottom of the stack, are designed to solve particular and very specific problems, that may not be known in detail to the upper layer algorithm.

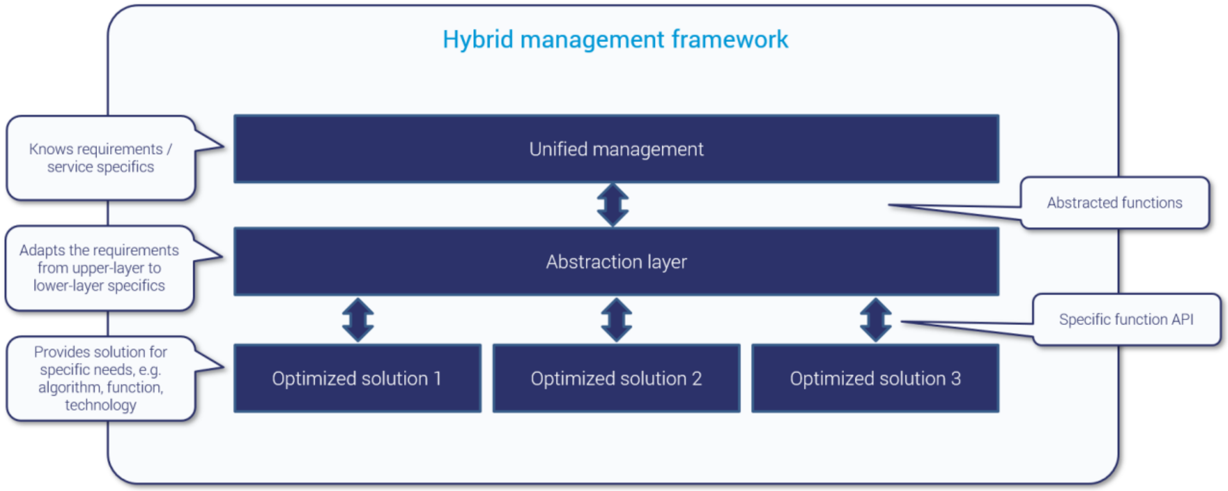

Figure 9. Generic framework – detailed design

By proper encapsulation, a recursive pattern can be created. Figure 10 shows this approach, where the optimized solution (lower layer scheme) can be further decomposed onto another level of hierarchy, embedding the even lower level optimized solutions into a module, which exposes only certain characteristics to the higher-level abstraction layer, which, in turn, is managed by higher level unified management.

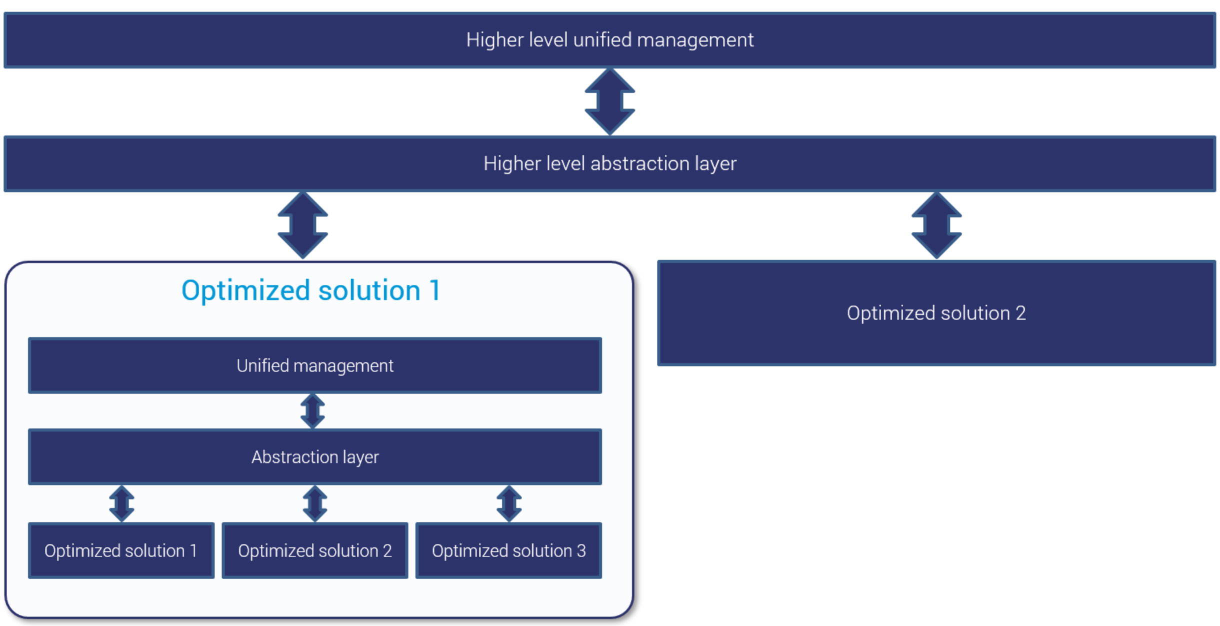

Figure 10. Unified framework – a recursive pattern

One straightforward example of a recursive pattern of this framework, investigated by the author of this dissertation, is where the MAC-layer scheduler coordinates the lower level specific schedulers, tailored to specific services (and those, in turn, being the optimized solutions implementing particular access schemes). This, however, can be managed by an upper layer traffic steering mechanism (the higher layer unified management), which controls the use of different radio access interfaces (e.g. LTE and NR under tight interworking scenario), from which each MAC is handling its radio resources using its set of schedulers, tailored to specific services. Such design allows for introducing a new optimized radio access scheme (e.g. dedicated for a new traffic type) and hiding the details from the Traffic Steering (TS) mechanism. In this case, the TS mechanism only gets a simplified set of parameters that need to be defined using common and generic functions. This makes the TS aware about new traffic types and algorithms present (i.e. the exposed version of the new scheme is simplified towards the upper layer). The TS, in turn, can have an implemented machine learning scheme to learn how and when to use the new mechanism.

Another example is focusing only on the MAC layer. The recursive scenario can be as follows: let us assume, that we have a RAN node supporting LTE and NR with a dynamic spectrum sharing. The utmost upper level scheduler distributes the users according to the capabilities and needs between those two RATs. The NR, however, could use multiple numerologies and support different access methods for different traffic types. Thus, there is yet another level, where the specifics of NR are separated from the NR-specific scheduler needing to coordinate the below mechanisms.

Yet another example can be the use of RSMs (see **[MD12]**), where the parameters are stored for the use of short-term low level RRM (like radio resource scheduler), at the same time providing the same aggregated and filtered parameters (e.g. received signal level or SINR values) towards the upper layer, which does not require to know exact values for every millisecond. In this design, the abstraction layer is a time-averaging filter, which provides a simplified set of characteristics to the upper layer, not interested into the details. Whenever a new set of parameters to embed in this scheme is provided, the same filter can be applied, not changing the design itself.

Similar example can be deduced from **[MD13]**, where REMs are utilized for different RRM schemes in a multi-operator scenario. The lower layer, an operator-specific set of parameters, is hidden towards the other operator. However, for common purposes, a simplified and anonymized version of the parameters is exposed to a common platform which enable both operators to utilize the same measurements and benefit from the other operator's parameters in a shared scenario, while still keeping the sensitive data locally using the proper simplification or filtering being the abstraction layer.

4.6 Summary of contributions provided in this chapter

The key author's contributions and proposals within this chapter are based on the following publications: **[MD4]-[MD13]** (supplemented by the additional materials covering some of the details **[MD1supp], [MD2supp]**):

- defining individual properties of the resource management framework for future wireless networks, required to capture the envisioned complexity, including hybridization, encapsulation, specification, abstraction and unification;
- proposing a unified and hybrid resource management framework design and extension, with the application of a recursive model, taking into account the complexity and various aspects provided in Chapter III, with examples on various network layers and potential extensions from the work already done;
- evaluation of the Spectrum Toolbox in the unified framework for future dynamic spectrum selection;
- proposal and evaluation of various Radio Service Maps, applied for future wireless networks;
- NB-IoT implementation analysis for incorporating it into the LTE framework.

Chapter V.

Use cases and case studies

This chapter presents how the proposed generic resource management framework from Chapter IV can be applied to specific use cases. The selected cases are based on the author's professional experience, gathered both during the commercial and non-commercial studies, and similar to Chapter III, the details and conclusions from those projects resulted in the following publications (grouped by subject):

- **Unified MAC layer design: [MD4] - [MD9]** (these concepts are discussed in the mentioned publications, while the detailed work of the author, that has been done, which resulted in those publications, is provided in supplementary material **[MD1supp], [MD2supp]**);
- **Unified Traffic Steering framework: [MD10]**, **[MD11]**;
- **Radio Environment Maps: [MD12]**, **[MD13].**

The purpose of this chapter is to describe the studied use cases, which prove the applicability of the proposed method for wireless systems on different levels in the radio resource management area.

5.1 Unified MAC and specialized access schemes

To provide the background of this use case, the author presents an overview of the related project, in which he was involved. The foreseen diversification of the service and device-class mix of future systems, as well as the related expansion of the requirement space called for proposal of a different approach to the radio interface anticipated by the 5GNOW project goals. New waveforms, the use of the Unified Frame Structure (see details in **[MD9]**), and Unified MAC with a mixture of synchronous and asynchronous traffic were major building blocks to support this approach **[MD8]**. The main aim of the 5GNOW project was to address several use cases with non-orthogonal waveforms. Few waveform approaches were proposed, such as BFDM, UFMC, FBMC and GFDM — all of them with disruptive advantages over OFDM and put in exemplary scenarios, such as service differentiation, spectrum agility, CoMP and real-time transmission **[MD7]**.

The author's main contribution to 5GNOW was to design the MAC architecture, enabling to fulfill the abovementioned goals. The basic idea behind the 5GNOW MAC, on top of this new approach to PHY layer, was that the developed non-orthogonal PHY layer waveforms and their specific structure will be incorporated into the design of control signaling on MAC layer, leading to different designs of access schemes for different waveforms. Such approach differs from typical schemes, where the transmitted signals have no impact on the design of the control channel **[MD5].**

The MAC scheduling framework, aimed to accompany the novel, non-orthogonal waveforms, with necessary algorithms and signaling, to assure that various types of traffic could be managed efficiently, taking into account trade-off between signaling and accuracy. An example, in this context, is the difference between MTC traffic vs. "bit-pipe" traffic, that are of different service types (e.g. MTC is typically a UL low bitrate, while "bit pipe" is typically a DL high bitrate). 5GNOW addressed these issues by incorporating them into the MAC design **[MD5].** The overall Unified MAC architecture, proposed by the author of this thesis, is presented in **[MD1supp]** and **[MD2supp]** and is based on two assumptions **[MD2supp]**:

- hybridity – the use of well-defined resource management mechanisms, targeting a specific or individual traffic type or application scenarios. This allows to use optimized algorithms, enabling to optimally fulfil traffic types' requirements and specific needs;
- hierarchy – the top layer selects traffic types that need to be served and then selects proper resource management algorithms (i.e. individual schedulers or procedures) to operate on low level. This allows the adjusting of policies and operation according to the current traffic situation (e.g. large MTC traffic during a specific part of the day or data download sessions in the evenings in the same or different places).

This concept defines the architecture, where there is a general MAC scheduler acting as a coordinator of individual schedulers, allowing to select proper scheduler (or access mechanism) and deals with proper communication between modes of internal schedulers **[MD2supp]**. This is a direct implementation of the framework, proposed as a contribution of this dissertation, as provided in Chapter IV.

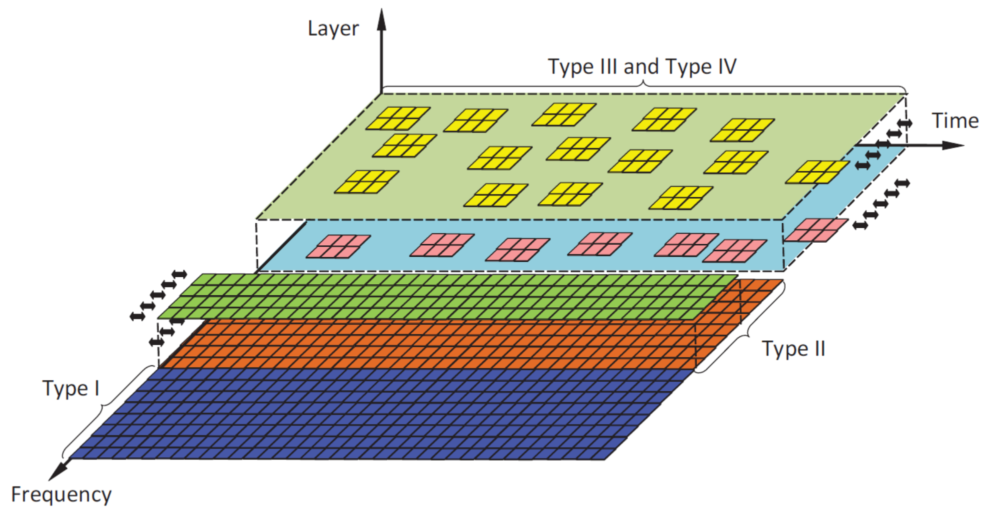

Figure 11. Unified Frame Structure. Traffic types: Type I – high-volume broadband traffic; Type II – traffic required relaxed synchronicity; Type III – sporadic small packets, Type IV – asynchronous transmission ([MD8] Copyright © 2014, IEEE)

In that context, multiple access schemes were proposed in **[MD8]**, **[MD9]**, **[MD1supp]**, **[MD2supp]** and applied to the new waveforms and Unified Frame Structure (see Figure 11) concept, to suit different applications or traffic types as follows:

- dynamic, channel adaptive resource scheduling for high-volume broadband traffic using standard resource scheduling mechanisms (e.g. Proportional-Fair (PF), Round-Robin (RR), maximum SINR), but for novel waveforms;
- Semi-Static/Semi-Persistent-Scheduling (SPS) for traffic requiring relaxed synchronicity (e.g. cell edges). From a MAC point of view, in this context it is necessary to decide on the amount of resources allocated for this type of traffic, since the scheduler will not adapt to a specific frequency. Therefore, another scheme is used, that does not require channel adaptive scheduling;
- One-shot transmission (low amount of data and pilots) with contention-like based approach, using D-PRACH for sporadic MTC traffic, enabling payload transmission in physical layer random access channel. For this scenario, MAC defines and steers the amount of resources dedicated for D-PRACH usage and use the dedicated procedure.

On the other end of the structure, as proposed in Chapter IV of this dissertation, a specific algorithm tailored to support a specific traffic type, was D-PRACH. The concept and description below comes from **[MD8]** and the detailed analysis (including traffic model configuration, analytical calculations) and simulation studies are provided in **[MD2supp] Section 4.2**.

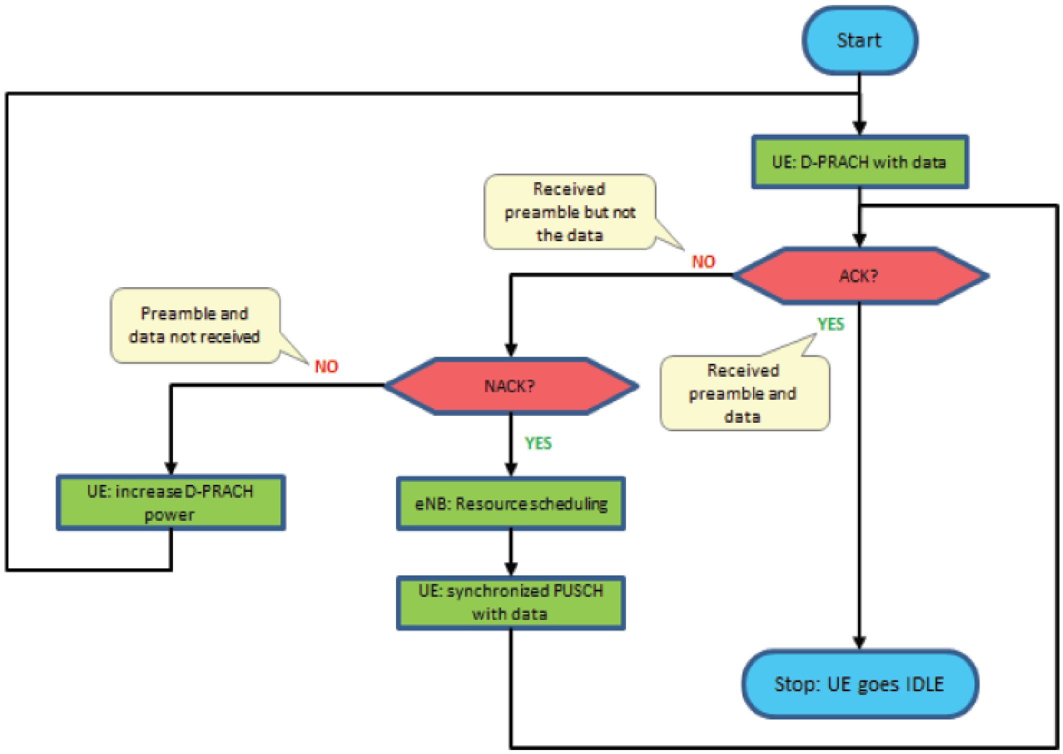

Figure 12. D-PRACH access procedure (proposed by author in [MD8] Copyright © 2014, IEEE)

A fast and scalable D-PRACH access architecture, using a suitable sparse signal processing concept, is proposed to efficiently deal with sporadic traffic and control signaling problem. Using this concept, the MTC traffic would be removed from standard UL data pipes with drastically reduced signaling overhead, improving operational capabilities and network performance, as well as user experience and lifetime of autonomous MTC nodes. The MAC implications are discussed in **[MD1supp]**. The author of this dissertation proposed D-PRACH procedure and operation, including Acknowledgement / Negative Acknowledgement (ACK/NACK) feedback for MTC application, which is depicted in Figure 12 and discussed in **[MD8]** with the details provided in **[MD2supp]**.

According to simulation results from 5GNOW project (example results from **[MD2supp]** are shown in Figure 13), one important parameter to be optimized within that procedure is the number of available PRACH preambles, with respect to the collision probability threshold and number of users. This is an exemplary aspect within the architecture, to be abstracted and provided by the specialized lower layer solution to the unified upper layer, which controls the overall resource usage and distribution between traffic classes.

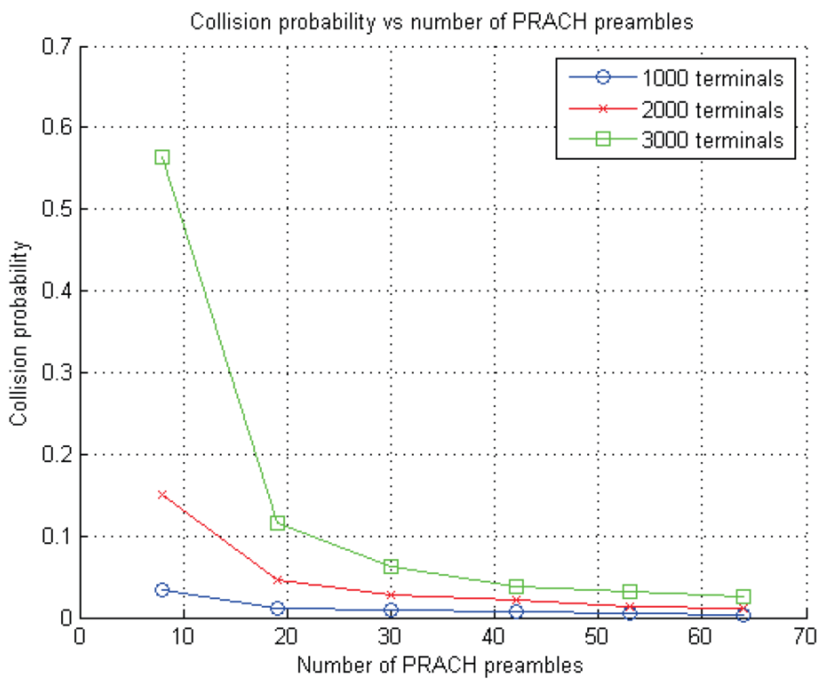

Figure 13. Collision probability vs number of PRACH preambles (figure from [MD2supp] – whole context is provided therein)

Figure 14 presents the mapping of the generic scheme, proposed in Chapter IV to this use case. The Unified MAC coordinates the distribution of the incoming traffic (based on its specifics) to the Unified Frame Structure resources. The specific traffic type is handled accordingly, using the dedicated waveform, accompanied by a dedicated access scheme (e.g. the MTC traffic is handled with the use of D-PRACH and one-shot transmission procedure, while the MBB traffic is dynamically assigned resources with the use of UFMC). The higher-level scheduler simply distributes the available resources to different traffic types, according to the "collective traffic demand" of that traffic type, while the lower level algorithms (access mechanisms) deal with individual transmissions on an instantaneous basis.

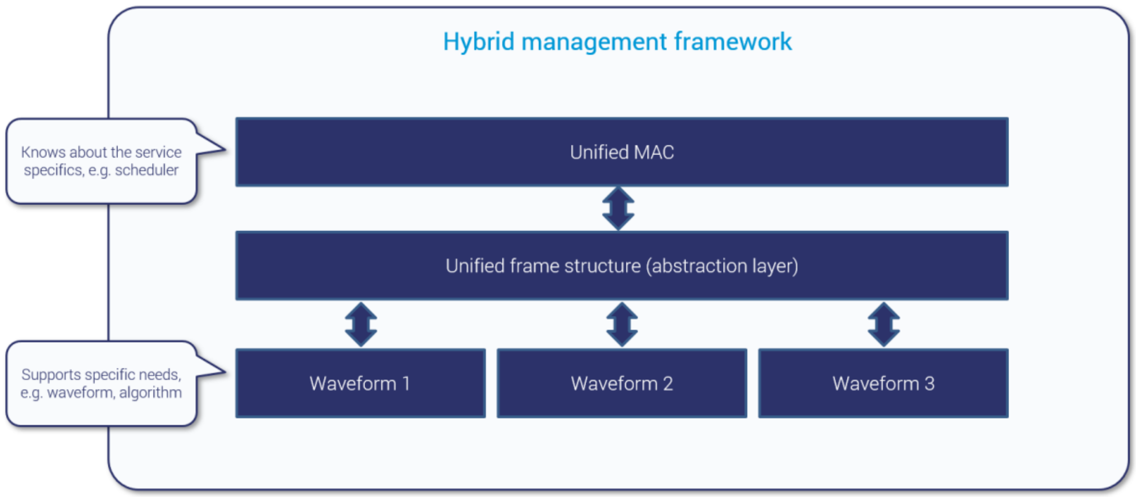

Figure 14. Framework usage – unified MAC and unified frame structure

Another application of this approach can be for the dynamic spectrum sharing between NR and LTE, in 5G context [29], where the unified MAC/scheduler (upper layer) selects, (based on the number of users, device capabilities and traffic types), the radio interface/PHY layer (see Figure 15 for this application).

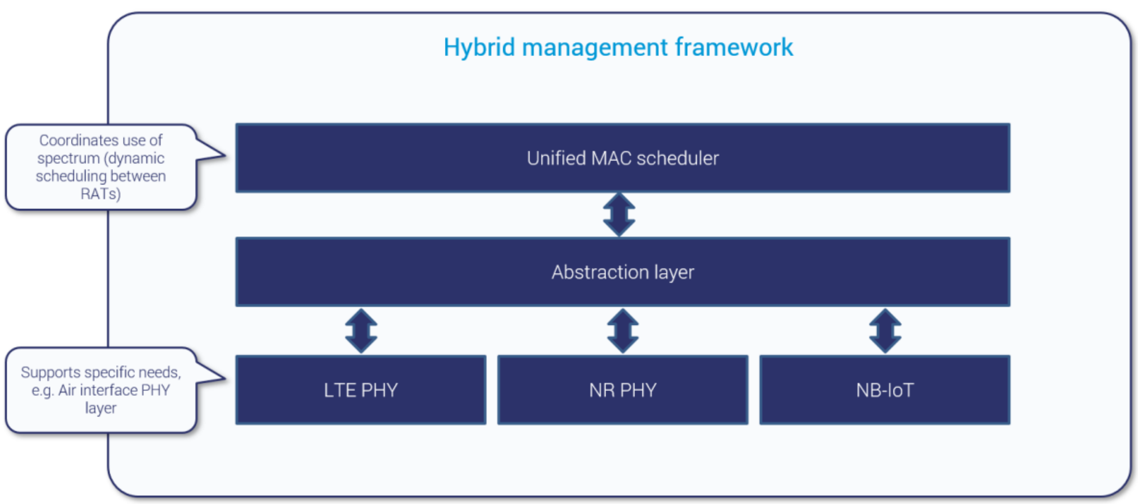

Figure 15. Framework usage – unified MAC and dynamic inter-RAT scheduling

The design could be as follows: under the lower layer of the hierarchical scheduler, there is another scheduler that knows the specifics of handling LTE-capable and connected users, and another scheduler to handle NR users (e.g. PHY layer numerology, radio resources, Modulation and Coding Schemes (MCS)). In this context, the unified upper layer scheduler does not have to know, that there is an LTE radio or NR radio. It has to be aware of the properties and capabilities to coordinate the distribution and assigned of the traffic, bearers or users to specific radio. When there is a new PHY layer introduced, the same approach is taken and it does not change the overall design.

5.2 Unified Radio Resource Management, Traffic Steering and SON

UE-specific cell selection is a multidimensional optimization problem. To properly assign radio links to users, a Traffic Steering engine needs to consider a set of inputs, e.g.: radio conditions, UE capabilities, available RATs and RAT-specific features, frequency bands and layers, cell load, QoS requirements, network and UE power consumption **[MD10]**.

The following two articles: **[MD10]**, **[MD11]**, analyze the RRM complexity in the context of HetNet and multitude of RRM and SON features, putting the traffic steering as the central point under the name Unified Traffic Steering (UTS) framework.

Selected aspects of this problem have already been addressed in prior work. The H2020 METIS-II project identified the need for a holistic approach in the "agile RRM" proposal, covering a multitude of use cases [30]. The H2020 COHERENT project addressed the Central RRM Coordinator framework [31]. RRM framework has also been proposed in H2020 Speed5G project [32], with centralized and distributed RRM, as well as abstraction layer, handling several RRM aspects. These concepts, however, focus solely on 5G, and do not cover the general aspects of 4G networks and the interworking needs. A coordination framework for HetNets was proposed in [33], however, addressing only a selected number of functionalities, including cell-sleeping and cooperative transmission mechanisms **[MD10].**

The UTS framework aims at orchestration of multitude of RRM-related functionalities for LTE-Advanced Pro. It assumes that a set of SCs under a single Macro-Node is managed by a single UTS control entity, which steers the user traffic via the available spectrum resources and RATs, using different coordination strategies and available features. The proposed scheme introduces a native and unified approach to the coordination and orchestration of radio access and TS-related mechanisms in multi-RAT networks for optimal radio resource utilization and efficient data delivery in mobile networks. The feature- and spectrum-coordination scheme is based on the network load. The strategies are updated according to MNO-policies by the use of RAN Management entity, which includes SON-related functionalities **[MD10].**

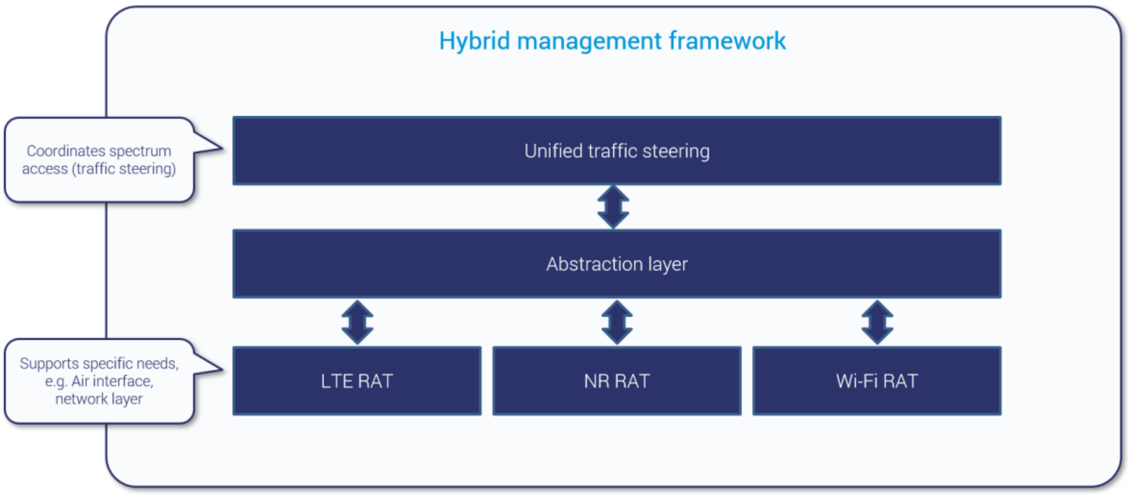

Figure 16. Framework usage – unified traffic steering

The design of the UTS focuses on orchestration of the available spectrum access mechanisms (the simplified scheme is shown in Figure 16). It also enables a scenario-specific feature prioritization and ranking to optimally utilize radio resources. UTS logic serves as an engine, coordinating TS mechanisms. This approach aims at avoiding network instabilities and contradicting actions being taken by individual RRM features when fragmented solutions are implemented. The UTS concept design enables the integration of new features, additional spectrum bands or novel spectrum licensing schemes, as investigated by the author in **[MD10]**.

The adaptive Unified Traffic Steering framework assumes an awareness of the traffic demand and the ability to optimize its power consumption within HetNet networks. This requires radio resource coordination on multiple levels: inter-RAT, inter-band, inter-site and inter-layer. The identified benefits from this approach are **[MD10]:**

- unified orchestration of TS-related RRM and SON functions to decrease the potential instability of network operation (e.g. avoiding contradicting actions between MRO and MLB);

- optimized usage of HetNet, in particular small cells, by using sleep mechanisms improving energy efficiency when there is no traffic;
- being future proof and easy integration of new RATs, spectrum bands and related features in the unified framework;
- providing unified decisions for traffic allocation to users being consistent through mobility support in multi-connectivity networks, thus supporting the requirement for enabling new services along with 5G introduction.

The individual considered features impacting the operation of the UTS are analyzed in detail in **[MD10]** and **[MD11]**. Based on the design, the individual feature can be incorporated above or below UTS logic. The framework allows to integrate new features in a consistent manner, by analyzing the inputs and outputs and defining what that particular feature has impact on. The common layer is RRC protocol, based on which, the actions have impact on the particular user situation. The framework design enables flexible adaptation to the particular scenario (see examples in **[MD10]**) and the availability of features in a specific place.

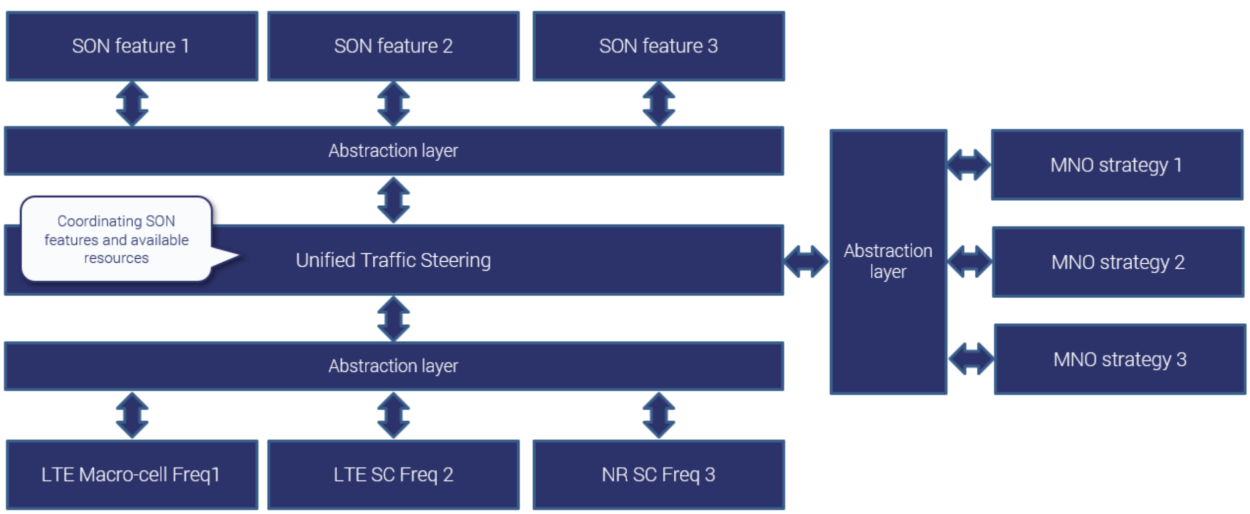

Figure 17. Unified Traffic Steering – multiple abstraction layers

The abstraction layers can be defined on multiple points (see Figure 17 for example design taking those into account):

- the UTS logic input is taking actions from multiple features;
- the MNO strategies are independent of the actual features and are based on common parameter being the network load which is technologically independent;

- the overall operation is independent on the actual and specific network layers and frequency bands or carrier frequencies;
- the configuration of the switching points between the individual features' operation can be MNO- and scenario-specific and is independent of the set of available features.

The recently discussed Artificial Intelligence (AI) and Machine Learning (ML) mechanisms fit in this framework. They can be utilized to observe the parameters and performance metrics on various abstraction layers, and decide which features are useful and which are not and for what scenarios. All of this could be done without prior definition of particular strategies. Another application of ML can be on the "load levels triggering state changes" to optimally assign thresholds and strategies based on the high-level operator's policies.

5.3 Generalization of radio environment maps

The author's findings on the topic of REMs are covered in **[MD12]**, **[MD13]**, which discuss different aspects of this technology, but provide common ground for generalization.

REMs (or generalized version, called the Radio Service Maps (RSM)) act as enablers for context-based resource management and fit into the overall picture of hierarchical system design to be combined with previously mentioned Unified MAC layer and Unified Traffic Steering framework. REMs are databases managed by a dedicated engine (e.g. a REM manager). This approach is in line with the concept of RAN virtualization, where network functionalities are separated from the underlying hardware platforms [34]. The successful implementation of RAN virtualization relies on orchestrating functions, together with managing storage, databases and hardware appliances **[MD13].**

As various types of data may be stored in the databases, the key role of REMs is to deliver accurate and detailed information on numerous environment's features (see Figure 18). With the use of REMs, the "context-aware communication" can be implemented, where rich context information is utilized for the optimization of various RRM functions (e.g. interference management, traffic steering, load balancing etc.). The information about available spectrum at a certain location is stored in dedicated repositories and can be accessed by an authorized player (e.g. an operator) or user (such as UEs or base stations). It may be then correlated with other types of information at the same location to make an optimized decision for a given criterion **[MD13]**.

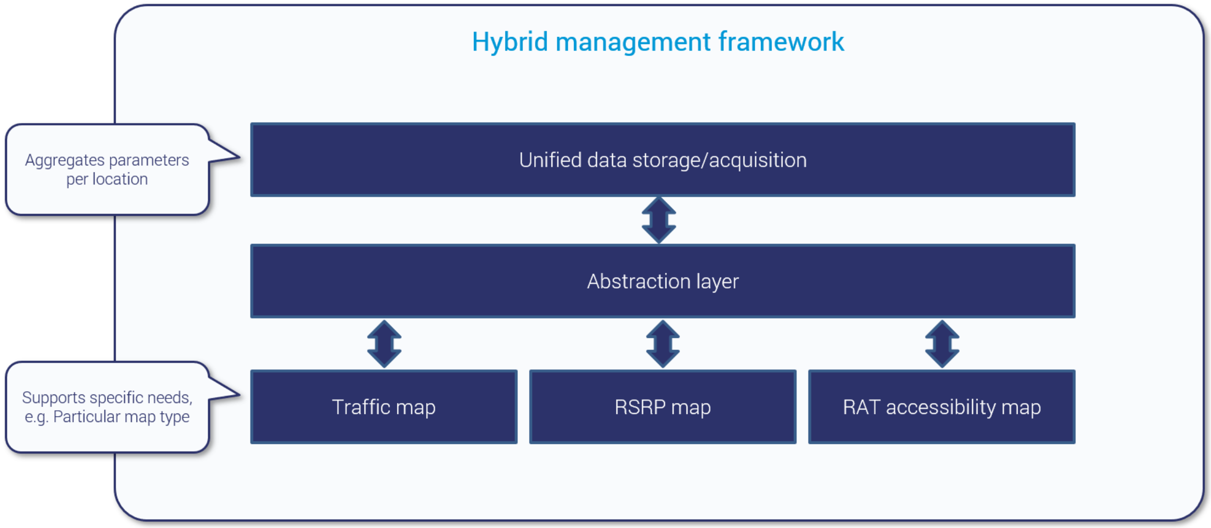

Figure 18. Framework usage – radio service maps

REMs (or RSMs) aim at reducing the amount of data acquired from different Measurement Capable Devices (MCDs) to a reasonable (manageable) size, while the data may need to be pre-processed and filtered without losing spatial or temporal resolution. Assuming this can be accomplished, a recursive RSM pattern, enabling a layered/hierarchical RSM solution, may be feasible **[MD12].**

The first article mentioned in the beginning of this section, namely **[MD12]** presents Multi-Dimensional RSMs (MD-RSMs), which builds on an extension of multi-layer REMs [35],[36], used to store, identify and correlate spatially related information of different KPIs for mobile wireless networks. The MD-RSM is presented as the key enabler for efficient future system, by helping to reduce the amount of required measurements reported by UEs, by utilization of cross-correlation of the maps, in the context of novel technologies, like user centric networks, mmWave spectrum, cloud, big data, holistic traffic steering and automated radio resource orchestration (an extension of SON) **[MD12]**.

An RSM stores measured or provided parameters in relation to user positions in space, time and frequency. In general, RSMs can be split into two groups: one related to network configuration and deployment (radio signal strength, spectral efficiency, available RATs or radio links); and the other, network-independent (like traffic type or velocity) **[MD12].**

An application of "recursiveness", mentioned in Chapter IV within RSM, is provided in the context, where the same information is collected and utilized on different levels for different purposes. For instance, if there is a need to operate on the maps locally, but with very fast adaptation (e.g. on a millisecond basis, for dynamic scheduling) – there is a low level RSM scheme. At the same time, when the same information is needed globally, however, on a different timescale (lower adaptation rate needed, e.g. for network layer optimization), the approach can be to aggregate that on upper level (losing some accuracy, which is not required on that level), abstracting the information by filtering data. However, the important aspect is to not require redesigning of the whole system for using the same data. Therefore, the filtering mechanism could be independent of the type of information.

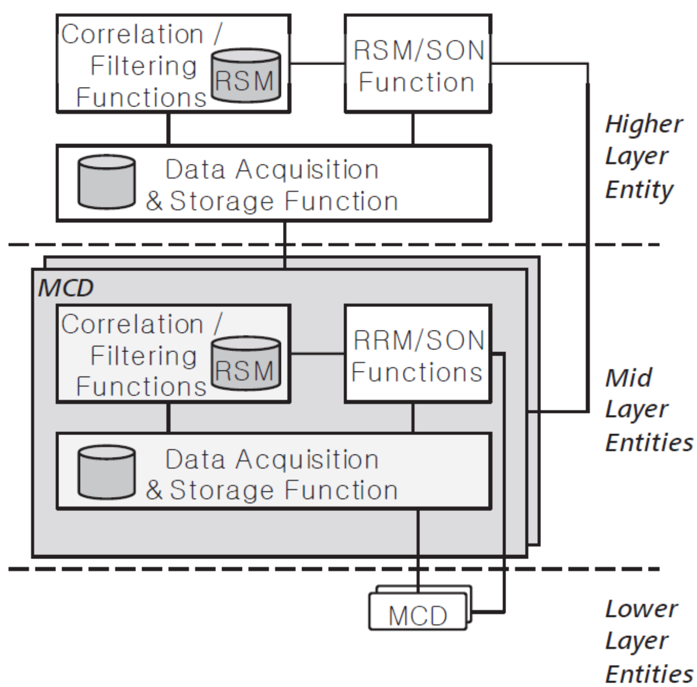

Figure 19. Example of recursive RSM architecture ([MD12] Copyright © 2017, IEEE)

Each recursive instance of RSM architecture (see Figure 19 and **[MD12]** for RSM recursive architecture details) pattern will acquire data from MCDs on a layer below and comprise of:

- data acquisition and storage function: collecting and storing data from several MCDs;

- MCDs: terminals, sensors, IoT devices and base stations, acquiring different types of information about the radio environment;
- filtering/correlation functions: operating on the stored data acquired from MCDs on the layer below, effectively providing relevant RSMs to RSM users or RSM instances on the layer above;
- RSM users: RRM/SON functions operating on the available RSM data (e.g. SON function – energy saving, capacity optimization; RRM-high function – traffic steering; RRM-low function – scheduling).

The second article, **[MD13]**, discusses the multi-operator application of REMs in the context of spectrum sharing scenario. In the considered case, each operator possesses their own REM-based spectrum management system (a REM-subsystem), consisting of private and shared databases. The public database is created in such a way, that information originated in one network may be shared, at request, with other REM-subsystem, as per mutual agreement **[MD13]**.

In this scenario, one MNO owns some spectrum resources and offers its services to outdoor users only. This MNO offers to share resources with other players to provide service to indoor users. Different approaches to spectrum sharing are elaborated in this work, ranging from static (but REM-based licensed network protection), to dynamic protection, based on detailed context information (e.g. an interference report providing the measure of intra-network interference) to address the issue of mutual interference between collocated networks' control. REM database is an entity facilitating the utilization of context information in this environment **[MD13]**. Depending on the application and used algorithm, the example results shown up to 10x higher average throughput when applying the contextual knowledge using the REM-based algorithms, as compared to the situation without the REM measurements, for indoor scenarios. At the same time, the resulting impact on the outdoor users (the ones, which transmission shall be protected) decreased only by a maximum of 10%, showing the significant gain of using REM. Detailed simulation results are provided in **[MD13]**.

In the proposed REM subsystem (see Figure 20), there are interfaces allowing high level of abstraction, namely: an interface used for message exchange between separate REMsubsystems; an interface to communicate with the legacy network of a certain operator; an interface for sensing modules enabling proper measurement collection **[MD13]**. In the considered use case, a shared REM-based management system (denoted as 3rd party) is used for spectrum management inside the building and may be managed by an MNO or theoretically may be in possession of the building owner. Apart from that, each REM-subsystem is a part of the whole network management system (NMS), thus dedicated interfaces between the REM and Network domain have to be maintained **[MD13]**.

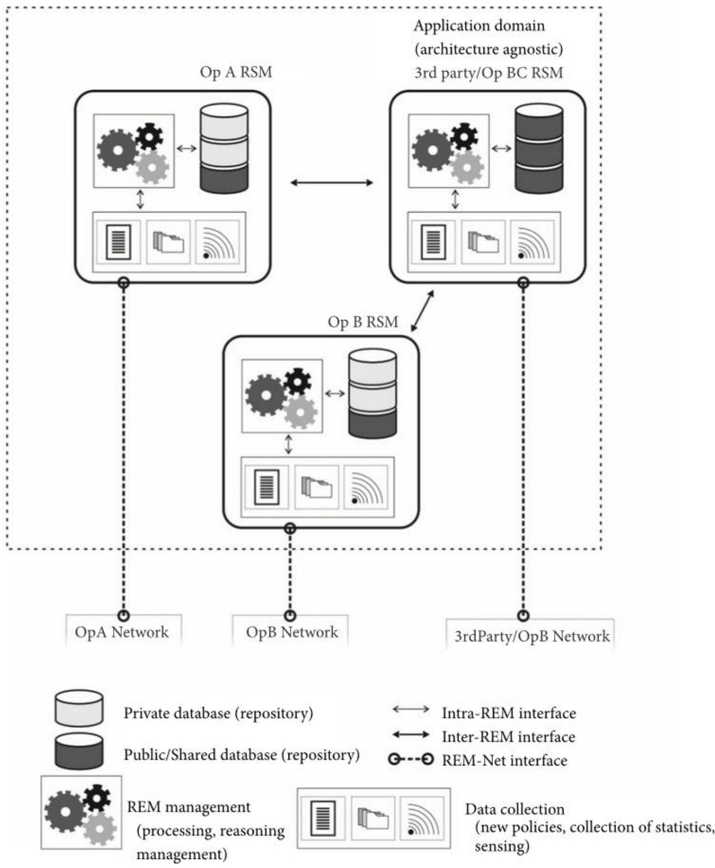

Figure 20. REM architecture for multi-operator scenario ([MD13] Copyright © 2018 Paweł Kryszkiewicz et al.[7])

Furthermore, relating the solution presented in **[MD13]** to the proposed framework from Chapter IV, it presents the common architecture for multiple scenarios, thus fitting into the concept of hybrid and hierarchical. The solution from **[MD13]** fits the proposed architecture from Chapter IV, due to unified handling of different aspects, such as:

- sharing methods: static, semi-static, dynamic;

- REM sharing: shared between operators, shared with the third party, shared between operators and third party;
- different sharing technologies: including LSA, Citizens Broadband Radio Service (CBRS) and co-primary sharing.

5.4 Summary of contributions provided in the chapter

The key author's achievements and proposals within this chapter are based on the following publications: **[MD4] - [MD13]** (supplemented by additional materials covering some of the details on Unified MAC **[MD1supp], [MD2supp]**):

- providing an analysis of the applicability of the proposed resource management framework from Chapter IV in concrete use cases, studied by the author along various projects, capturing the different layers of RRM area, including Unified MAC layer, Unified Traffic Steering framework and generalized REMs;
- the contributions to designing the individual items within the individual sections, like D-PRACH procedure design, simulation studies of Unified MAC, UTS Framework design, Unified MAC design, architecture of RSMs;
- providing the proof of the applicability of the proposed resource management proposed in Chapter IV scheme for different layers in wireless systems, including low level RRM (Unified MAC layer), high level RRM & SON (Unified Traffic Steering framework), network measurements layer – (Radio Environment Maps).

Chapter VI.

Future work – generalization of the approach

The extension of the framework proposed in Chapter IV could be to merge the Unified MAC design with Unified Traffic Steering and Generalized REM, being the potential future work. The RRC level control (higher level RRM) can be independent from the lower layer RRM (MAC scheduling, PC, interference management). The selection of a particular RAT (e.g. LTE or NR) can be based on the common set of parameters. Once the RAT is selected, the proper scheduler can be in operation, and feedback can be provided to adapt the upper layer Traffic Steering. The other option is that the UTS can decide to use several nodes and with different RATs (e.g. MCG with LTE and SCG with NR) for one user and another configuration (e.g. MCG on NR and SCG on LTE) for another user. In this context, the unified scheduler needs to coordinate the resources used for both users, without looking on the specifics of each radio interface. Both of those can be supported with REM measurements, using a hierarchical approach as both mechanisms (MAC and TS) operate on different timescale, but both need the same type of measurements, namely the signal level. In the above context, where Unified MAC layer is combined with Unified Traffic Steering, the important aspect is *where to put the abstraction.* Unified MAC is focusing on a set of users (MAC layer provides access to multiple users in a single cell), while UTS is focusing on a specific user (TS decides which cells to assign to a particular user). Unified MAC operates on various lower layer PHY schemes, while UTS uses a common set of RRC procedures and operates on a different set of RATs and features. Those facts actually provide a guideline for the abstraction layer. REM, in this context, provides inputs to both being on a side.

Additionally, when combining the RRM levels, there is a need for a feedback and interaction between both (MAC and RRC) to make optimal decisions. For instance, the Unified MAC shall provide information on the usage statistics and performance measures to the UTS, so the proper decisions which RATs (or layers) shall be used for a certain user. This is where another type of scheme could fit, namely the "measurements framework", where one element comprises of the internal measurements (MAC-to-RRC feedback), and the other one being REM, where the gathered information comes from the MCDs. Summarizing, the author claims that the unification, hybridization and hierarchization can be the approach for future network management, specifically for “RRM low”, “RRM high”, SON and network orchestration.

The other direction of future work is to generalize this approach further and extend to higher layers, including transport network, core network, IP layer, and the service layer (e.g. Voice-over-Internet Protocol (VoIP) or IMS), where aspects, like load balancing and traffic steering, play important role as well. The examples of “SON for EPC” are presented in [37] and include: Mobility Management Entity (MME) load balancing and offloading to manage connections between the signaling nodes, paging and tracking area list management and optimization, routing optimization for latency decrease between Serving Gateways (SGW) (SDN-like), energy saving management for underutilized SGWs. The examples for “SON for services” are also presented in [37] and include: end-to-end voice quality improvements, and IMS nodes load balancing for voice calls. Those types of functionalities are already being addressed in the context of 5G, when speaking on SDN and NFV and their respective frameworks. The SDN-based networks abstract the data-plane from the management and control, while NFV abstracts the network functions from the underlying infrastructure, which suits the general concept of unified and hierarchical framework presented in this dissertation. In this context, softwarization of the core networks is already present in 5G context, by means of Service-Based Architecture (SBA), where 3GPP already defines the abstraction and common communication platform, based on Hypertext Transfer Protocol/2 (HTTP/2) and Representational State Transfer (REST) Application Programming Interface (API) [8].

Yet another aspect from the 5G scope, to be further studied in the context of hybrid and hierarchical management framework, is network slicing and its application in NG-RAN [38]. Some of the recent works on this topic included virtualized RAN and dynamic RAN slicing, and can be found in [39], [40], [41]. In the context of slicing, three areas in the RAN management could be defined, namely: intra-slice management – “slice-specific” (optimization of resources for a certain slice – i.e. all users being connected to a given slice), inter-slice management – "slice-unified" (e.g. MAC scheduler providing access resources to multiple slices and needing to distribute them among slices) and slice-independent management – "slice-agnostic" (e.g. traffic steering – focusing on a certain user, which can be connected to multiple slices at once). This should be then followed by analysis of merging with corresponding core network aspects (namely, 5G network slicing) and management and orchestration layers, as imposed by NFV architecture.

Chapter VII.

Summary and conclusions

Concluding the aspects discussed in this work, it can be seen that the management of the network resources, within the complexity visible in today's mobile network and ongoing developments, should be addressed in a generic manner, to be able to operate those networks efficiently.

The author discusses the fragmentation of the various aspects of the current networks in Chapter III, including frequency bands, bandwidths and access methods, system features, RATs, SON functions and traffic types. The evolution of those is provided and is clearly showing that the system landscape is getting more and more complicated with the evolution from 4G to 5G. A significant step in this aspect is the introduction of 5G, bringing new concepts to mobile networks, including new services and techniques. Another aspect, important to mention, is the feature-richness, provided by the recent advancements in LTE, which addresses the needs of today's networks with more and more capabilities, build on the basic LTE framework from 2008. The discussion is summarized with the proposed Spectrum Toolbox, which allows to categorize different aspects of the complex system's landscape.

Management of such complicated networks in not an easy task, especially because the development does not stop, while *backwards compatibility* is the basic requirement in practically implemented systems. Because of that, it is not possible to design a new system to just cope with the new requirements from scratch. The result of the backwards compatibility requirement is the need to add new items to the existing systems on different levels (e.g. new RAT, new functionality, new waveform, new algorithm, new service), which requires adjusting the existing networks.

The adaptation of the existing system to the new requirements and functionalities is a complex task, and can be solved by one of the possible approaches: universal (one design) – where all of the different requirements and services are captured by a single scheme and, by using reconfigurations, they can be optimized; individual and specific – each of the new services is getting a new system version – this approach is very costly and creates fragmentation in the market; unified and hierarchical – the proposed one, where the specifics are separated from the system's coordination and new items can be added as "plugins" to the architecture.

The author of this dissertation claims that, based on his experience from 5G air interface design studies, Unified Traffic Steering and REM projects, it is possible to generalize the approach and provide a framework to cope with those challenges. The proposed management solution is based on three main components: *specialized solutions* for individual requirements, exposed to the *unified generalized layer,* with a proper *abstraction* layer. Thus, the resulting framework becomes hybrid and aims at the simplification of the introduction of new elements. The unified layer is not required to be aware of the specifics and "names" of the individual lower layer solutions. It needs to know the properties, applications and capabilities of the lower layers, abstracted in a common manner. By this, the upper layer becomes a coordinator to apply the lower layer solutions to a specific use case. The author proposes to create the framework using the following actions: encapsulate (the solution), simplify (the solution), hide (the solution), expose (the simplified version of the solution), and use the coordination mechanism. As an example, instead of proposing three specific options with different names (like LTE-NR tight RAN integration) or specific band combinations (e.g. for CA application), provide the description of properties and capabilities. Additionally, the coordinator could have embedded AI mechanisms to learn how to use new features and provide feedback on which solutions are not working and guidance on the improvements.

To capture the fact that different aspects can be fitting on different levels, the recursive pattern is also provided, which allows to extend the framework towards real hybrid systems. An example can be seen on the radio interface, e.g. new waveform can be managed by a unified MAC_1, handling a single RAT, while when new RAT is designed, it can be captured on an upper layer unified MAC_2, which encapsulates the unified MAC_1 and adds the new RAT on the side. This requires to create abstraction layers on multiple levels, which allows to separate different aspects and plug-in new features, depending on where they fit optimally.

Examples of the application of this approach were provided in chapter V, where the author gathered the works from various projects, including the Unified MAC layer, Unified Traffic Steering and Radio Environment Maps. Based on this, the author claims that it is possible to extend and generalize further this approach towards other network layers, especially in the era of network "softwarization", brought by the recent developments and the introduction of 5G, like transport or core network. The consideration on this is provided in Chapter VI.

Summary of author's achievements and proposals

The key authors contributions and proposals within this dissertation:

- providing an analysis of the current network features and elements for LTE and its evolution and 5G systems (based on **[MD1]**, **[MD2]**, **[MD3]**);
- contributing to a proposal for a scheme for classification of different aspects of current and future mobile wireless systems called the Spectrum Toolbox, serving as an input to create a resource management framework (based on **[MD1]**, **[MD2]**);
- proposing a definition and design of the unified and hierarchical resource management framework to cope with the current and future networks' complexity and optimized operation (based on **[MD4]**, **[MD5]**, **[MD6]**, **[MD7]**, **[MD8]**, **[MD9]**, **[MD10]**, **[MD11]**, **[MD12]**, **[MD13],** supplemented by **[MD1supp]**, **[MD2supp]**);
- analyzing the applicability of the proposed framework within the three use cases on different levels of radio resource management (based on **[MD4]**, **[MD5]**, **[MD6]**, **[MD7]**, **[MD8]**, **[MD9]**, **[MD10]**, **[MD11]**, **[MD12]**, **[MD13]**, supplemented by **[MD1supp]**, **[MD2supp]**);
- the contributions to designing individual items within individual sections, like: D-PRACH procedure design, simulation studies of Unified MAC, UTS Framework design, Unified MAC design, architecture of RSMs (based on **[MD4]**, **[MD5]**, **[MD6]**, **[MD7]**, **[MD8]**, **[MD9]**, **[MD10]**, **[MD11]**, **[MD12]**, **[MD13]**, supplemented by **[MD1supp]**, **[MD2supp]**);
- proposing future work to extend and further generalize the proposed solution to other network layers.

References

Own publications (constituting the basis for the PhD dissertation)

[MD1] M. Szydełko, M. Dryjański, "Spectrum Toolbox Survey: Evolution Towards 5G", CrownCom 2016, Grenoble, France, 05.2016. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Vol. 172. Springer, Cham, DOI https://doi.org/10.1007/978-3-319-40352-6_58, ISBN: 978-3-319-40352-6

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[MD2supp] FP7 5GNOW, "Final MAC/Networking Concepts", Deliverable 4.2, March 2015

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[1] 3GPP RP-151569, "Release 13 Analytical View Version," September 2015

[2] 3GPP TR 37.843, v12.0.0, "Study on WLAN-3GPP Radio Interworking," December 2013

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Part B

Copies of publications, declarations and supplementary documents

Articles published in journals and magazines

1. G. Wunder, P. Jung, M. Kasparick, T. Wild, F. Schaich, Y. Chen, S. Brink, I. Gaspar, N. Michailow, A. Festag, L. Mendes, N. Cassiau, D. Kténas, **M. Dryjański**, S. Pietrzyk, B. Eged, P. Vago, F. Wiedmann, *"5GNOW: Non-Orthogonal, Asynchronous Waveforms for Future Mobile Applications"*, IEEE Communications Magazine (Vol. 52, Issue 2, February 2014)

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4. P. Kryszkiewicz, A. Kliks, Ł. Kułacz, H. Bogucka, G. Koudouridis, **M. Dryjański**, *"Context-Based Resource Management and Orchestration in 5G Wireless Access Networks"*, Hindawi Wireless Communications and Mobile Computing, Vol. 2018

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1. G. Wunder, M. Kasparick, S. Brink, F. Schaich, T. Wild, I. Gaspar, E. Ohlmer, S. Krone, N. Michailow, A. Navarro, G. Fettweis, D. Ktenas, V. Berg, **M. Dryjanski**, S. Pietrzyk, B. Eged, *"5GNOW: Challenging the LTE Design Paradigms of Orthogonality and Synchronicity"*, IEEE VTC, Dresden, Germany, 2-5 June 2013

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4. T. Wild, G. Wunder, F. Schaich, Y. Chen, M. Kasparick, **M. Dryjanski**, S. Pietrzyk, N. Michailow, M. Matthé, I. Gaspar, A. Navarro, L. Mendes, A. Festag, G. Fettweis, J. Doré, N. Cassiau, D. Kténas, V. Berg, B. Eged, P. Vago, *"5GNOW: Intermediate Transceiver and Frame Structure Concepts and Results"*, EuCNC'14, Bologna, Italy, 23-26 June 2014

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Book

1. M. Rahnema, **M. Dryjanski**, *"From LTE to LTE-Advanced Pro and 5G"*, Artech House, US, 2017, 376pp, ISBN: 978-1-63081-453-3

Supplementary documents

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